Minimum energy efficiency standard (MEES) requirements and the impact on the UK hotel buildings stock

Minimum Energy Efficiency Standard (MEES) Requirements and the Impact on the UK Hotel Buildings Stock

Shiva Amirkhani

Student Number: 21377016

A thesis submitted to the University of West London

for the degree of PhD

Supervisors:

Professor Ali Bahadori Jahromi, School of Computing and Engineering

Dr Anastasia Mylona, CIBSE

February 2022

Declaration of Authorship:

I, Shiva Amirkhani, declare that this thesis titled, '*Minimum Energy Efficiency Standard (MEES) Requirements and the impact on the UK Hotel buildings stock*' was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or processional qualification except as specified

Signed: ...Shiva Amirkhani...

Date: ...January 2022...

Abstract

In an attempt to reduce the greenhouse gas emissions from the building sector, in 2018, the UK government introduced the Minimum Energy Efficiency Standard (MEES). The regulation enforces a minimum Energy Performance Certificate (EPC) rating of E or above for commercial buildings before they can be sold or rented. Hotels – one of the most energy intensive building types – are among those affected by MEES. This research investigates the contribution of MEES requirements to effectively reducing CO_2 emissions from the hotel sector in England and Wales.

In this study, a quantitative research approach is employed to address the research questions. Dynamic simulation software tool, EDSL TAS, is used for running the EPC calculations for four different hotels. Through rounds of simulations, analysing both the simulation results and measured data for the hotels and the evidence from literature, the study finds potential sources of uncertainties within the current non-domestic EPC for hotels. Overestimation of domestic hot water (DHW) and underestimation of cooling energy use are among the main uncertainties, both of which stem from the standard assumptions imposed by National Calculation Methodology (NCM). The impact of these uncertainties goes beyond the cases in this work; all hotels applying for an EPC in the UK are affected. Combined with further findings such as the significant impact of the DHW systems' efficiency on the EPC rating of a hotel, a major risk is revealed: failing to receive the expected reductions in energy consumption and CO_2 emissions by improving the EPC rating. This can be detrimental both to individual stakeholders and national goals for emissions reduction policies.

In addition to practical implications for both hotel industry and the UK's energy policy makers, this study also contributes to the existing knowledge as the field of non-domestic EPCs has been under-researched. This thesis is a first attempt to achieve a clearer picture of the UK's non-domestic EPC as the main character in the MEES policy. The author is of the idea that the main contribution of this study is highlighting the fact that due to the shortcomings of the existing EPC framework, the effectiveness of MEES in reducing the CO_2 emission from hotels is at risk. Unless these issues are rectified, actual contributions from MEES in the hotel sector may be considerably less than expected.

Table of Contents

List of Figures

List of Tables

List of Acronyms

AHU	Air Handling Unit
APR	Air Permeability Rate
ASHP	Air Source Heat Pump
BER	Building Emission Rate
BRE	Building Research Establishment
CBECS	Commercial Building Energy Consumption Survey
CHP	Combined Heat and Power
CIBSE	Chartered Institute of Building Services Engineers
CO_2	Carbon dioxide
CHW	Chilled Water
C_v(RMSE).	Coefficient of variation of the Root Mean Square Error
CoP	Coefficient of Performance
DCLG	Department for Communities and Local Government
DER	Distributed Energy Resources
DHW	Domestic Hot Water
DSY	Design Summer Year
EDSL	Environment Design Solutions Limited
EEBPP	Energy Efficiency Best Practice Programme
EER	Energy Efficiency Rate
EPBD	Energy Performance Building Directive
EPC	Energy Performance Certificate
EU	European Union
EUI	Energy Use Intensity
FCU	Fan Coil Unit
Gt	Gigatonnes
HDD	Heating Degree Days

HVAC	Heating, Ventilation and Air Conditioning
IES	Integrated Environmental Solutions
IPMVP	International Performance Measurement and Verification Protocol
LTHW	Low Temperature Hot Water
MBE	Mean Bias Error
NCM	National Calculation Methodology
PEC	Primary Energy Consumption
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
TER	Target Emission Rate
TRY	Test Reference Year
UK	United Kingdom

به نام خداوند بخشنده مهربان

I dedicate this thesis to

My sisters, Bita and Sara,

For their unconditional love, their constant support

and, for being my best friends.

Acknowledgement

I would like to express my sincere gratitude to my supervisory team and project sponsors, Dr Anastasia Mylona, Dr Paulina Godfrey and Mr Darren Cook, whose expertise, feedback and guidance over the past three years have been invaluable. I learned a lot from your thoughtful comments and recommendations on my work.

I would particularly like to thank my principal supervisor, Professor Ali Bahadori Jahromi, for his constant support and guidance. Thank you for trusting me to complete my research independently while making the time for me whenever I needed it. Thank you for letting me gain experience on teaching and presenting and all the other opportunities I was given. Beyond all the academic and professional guidance I received from you, your support and reassurance during the final months of this work as I was going through the hardest times of my life, will always remain with me. I am sincerely grateful.

I am grateful to my family, especially my sisters, Bita and Sara. They have been my greatest supporters and without them I would never be able to stand where I am standing now…

Bita, you have always encouraged me to fight for what I wanted and to never give up. You gave me a home when I needed it most. You listened to me whenever I felt sad or scared and helped me to get back on my feet… Thank you for always being there for me. I hope I can do the same for Asal in whatever path she chooses for her life.

Sara, I have countless memories of the things you have done for me over the years, some of them are shining brighter in my mind … the time when I was seven and you would check on me to see if I had done my "mashq" or homework, the time when you would pack my lunch for school, and the day you promised me to support me through thin and thick so that I could pursue what I wanted… I will probably never be able to return your kindness, but I will remain forever grateful.

There is another person from my family that I would like to thank dearly, who has supported me like the kindest of brothers. My dear brother-in-law, Robin, thank you for having my back and believing in me all these years. Without your support, I could never be here.

And last but not least, I would like to pay tribute to my late brother, my dear friend, Ali, who left us too soon in November. Ali, for many years, you were part of our family. Every time I reached a milestone, you were among those I wanted to celebrate with. You helped me with my job, you ensured me you will look after things when I moved to the UK, and you were the happiest when I was accepted for this PhD. I wish you were here to see me finish it too... Ali, you will always live in our memories.

List of Publication

Amirkhani, S. *et al.* (2019) ‘Impact of Low-E Window Films on Energy Consumption and CO_2 Emissions of an Existing UK Hotel Building’, *Sustainability*, 11(16), p. 4265. doi: 10.3390/su11164265.

(From chapter 4)

Amirkhani, S. *et al.* (2020) ‘Impact of Adding Comfort Cooling Systems on the Energy Consumption and EPC Rating of an Existing UK Hotel’, *Sustainability*, 12(7), p. 2950. doi: 10.3390/su12072950.

(From chapter 5)

Amirkhani, S. *et al.* (2021) ‘Uncertainties in Non-Domestic Energy Performance Certificate Generating in the UK’, *Sustainability*, 13(14), p. 7607. doi: 10.3390/SU13147607.

(From chapter 6)

Under review:

Amirkhani, S. *et al.* (submitted in June 2021) ‘Key factors in determining the EPC rating of non-domestic buildings. Case studies of three UK hotels’, *Advances in Environmental Research*, *Techno Press*

Chapter 1 General Introduction

1.1 Overview

1.1.1 Background

In recent years, amidst increasing concern about the impact of global warming, the United Kingdom (UK) government has set ambitious targets designed to significantly reduce greenhouse gas (GHG) emissions. Specifically, an 80% reduction by 2050, measured against 1990s levels in the Climate Change Act 2008 (Committee on Climate Change, 2017). (At the time of writing this thesis, the UK Government set an even more ambitious target through the Sixth Carbon Budget; to reduce the emissions by 78% by 2035, to bring the UK more than three-quarters of the way to net zero by 2050 (UK Government, 2021)). Through the measures taken, the UK has reduced its emission by 40% from 1990 to 2019, while growing the economy (Climate Change Committee, 2021).

With the perceived role of anthropogenic activities in increasing the GHG levels (Cuce and Cuce, 2013), tackling the issue is important, and requires significant change across many sectors to make the necessary reductions while keeping the energy sector secure and competitive. It is believed that one of the most effective means of reducing the GHG emissions is energy efficiency (Pérez-Lombard *et al.*, 2009; European Commission, 2012). Analyses indicate that high energy saving potentials lies within the building sector (Cullen, Allwood and Borgstein, 2011; Bossmann, Eichhammer and Elsland, 2012) which makes a significant contribution towards energy consumption and energy related GHG emissions (Güçyeter and Günaydın, 2012; Pasichnyi *et al.*, 2019; von Platten *et al.*, 2019). In fact, it is estimated that building sector is responsible for up to 40% of final energy consumption (BPIE, 2011). In the UK, direct GHG emission from building were 87 $MtCO_2e$ in 2019, around 17% of the UK's total emission. By including indirect emissions, the share of building sector rose to 23%. In this context, direct emission results primarily from burning fossil fuel for heating (both space and water) purposes. The indirect emission in building sector refers to the electricity use. The share of domestic, commercial and public properties in building sector's direct emissions were 77%, 14% and 9%, respectively (Climate Change Committee, 2020).

Through the measures taken, the UK government has managed to demonstrate reductions in emissions alongside a growth in economy. For instance, in 2017, emissions from domestic sector have fallen by 19% compared to the 1990, while almost 5 million new homes were built during this period. The emissions from industrial and commercial buildings during the same period were reduced by 23% (DBEIS, 2019).

It is estimated that around 75% of the EU's 210 million buildings are energy inefficient and majority of them, i.e., 75%–85% of them will still be in use by 2050 (Fabbri, Groote and Rapf, 2016). Therefore, increasing the energy efficiency of building sectors has been the main focus of many public policies (IPEEC, 2014). Furthermore, compared to other sectors, the building sector's GHG emissions can be reduced with a lower cost (Bressand *et al.*, 2007). So much so that improved energy efficiency in buildings was once declared the cheapest means of CO_2 emission mitigation (Barker *et al.*, 2007).

With the expected increase in buildings' energy demand by 2050 (Souayfane, Fardoun and Biwole, 2016; van Ruijven, De Cian and Sue Wing, 2019; Zheng and Weng, 2019) international efforts for GHG mitigation have emerged in the form of policies and regulations adopted and introduced around the world.

Despite the differences, the policies aiming at increasing the energy efficiency of buildings can be divided in three overarching groups:

- Building codes/regulations: they are regulatory measures and compliance with their guidelines is mandatory, therefore they provide the minimum requirements
- Voluntary/certification schemes: these policies usually put forward standards and guidelines beyond the minimum requirement. They are also referred to as soft instruments (Annunziata, Frey and Rizzi, 2013; Allouhi *et al.*, 2015)
- Financial incentives: these are put forward to drive building owners to consider energy efficiency retrofitting in their property in the form of grants, loans, tax reductions and subsidies (Goeders, 2010; Annunziata, Frey and Rizzi, 2013; Allouhi *et al.*, 2015)

Given the extent of the problem, many countries are now focusing on the minimum yet mandatory requirements to tackle the issue. In line with global efforts, the UK government has introduced requirements for the energy efficiency of the new and existing buildings. While these efforts target both domestic and non-domestic buildings, reports suggest that non-domestic sector shows higher resistance towards adopting measures for improving the energy performance (Ling-Chin *et al.*, 2019). This can be due to different reasons, for instance higher percentage of co-ownership in non-domestic sector and shorter term of tenancy/occupancy compared to the domestic sector. The latter is especially important as investments in improving the energy performance typically are profitable over the longer terms (Charalambides *et al.*, 2019).

In the UK, the non-domestic buildings are responsible for 17% of annual energy consumption and 12% of GHG emissions (CIBSE, 2017a). In order to reduce the CO_2 emissions from non-domestic buildings, the Government introduced the Minimum Energy Efficiency Standards (MEES), which came into effect in April 2018, targeting the energy performance certificate (EPC) of commercial buildings situated in England and Wales. The regulation, mandates the owners of commercial buildings to ensure a minimum EPC rating of band E for their property, before making any new sale or rent-out deal on that property (BEIS, 2017). Given that until recent years, there was no legally binding requirement in place for this matter, MEES is the first official measure that mandates action by making it against the law to make a new deal (letting or selling) on a non-compliant building from April 2018 and continued lettings of assets by 2023 (Sayce and Hossain, 2020). While MEES was considered an important initiative aimed at reducing the CO_2 emission from the non-domestic sector, it was also feared that it could have been viewed as financial and executive burden for those involved in the property market (Sayce and Hossain, 2020).

1.1.2 What is EPC?

EPC is an information tool showing how energy efficient a building is compared to other buildings of similar use. It classifies buildings on a banded scale from A to G based on annual CO_2 emission, where A (or A+ for non-domestic properties) is the most efficient in terms of <u>likely</u> fuel costs and CO_2 emission (MHCLG, 2020). The rating is accompanied by a numeric indicator, providing further differentiation within bands (BRE, 2006). It is important to know that EPC estimates the <u>theoretical</u>, as-designed energy performance of a particular building based on the building fabric specification, its services such as heating, cooling, and lighting and standard profiles for its internal activities and it doesn't provide any information on building's operation in practice (Lewry *et al.*, 2013).

As it will be discussed in more details in chapter 2, EPCs were first introduced in Energy Performance Building Directive (EPBD). The main objective of the Directive was to encourage the Member States to effectively improve the energy performance of their building stock through cost effective measures. This goal was pursued through the following aspects:

- Setting up a methodology for calculation: Member States are required to establish a methodology for calculating the energy performance of buildings in which all the factors affecting the energy use are considered.
- Regulation for minimum energy performance: there should be regulations designating minimum energy performance requirements for new buildings and the existing buildings going through refurbishments
- Energy performance certificates: requirements for applying for energy performance certificate after the end of the construction phase, selling or renting a property
- Inspection of boilers and air conditioning (BRE, 2006)

The first three aspects are directly related to the EPCs. As it is discussed further in Chapter 2, the EPBD left it to Member States to decide on the methodology for calculating the energy performance of their building sector. Most European countries opted for whole building thermal analysis, using thermal modelling and energy simulation tools (Intelligent Energy Europe, 2008). The methodology for conducting EPCs in England and Wales has been in effect since 2008. The main software tool for conducting the analysis in the non-domestic sector is Simplified Building Energy Model (SBEM). Thermal modelling and simulation tools help in assessing the energy performance of a building through mathematic equations associating the building's physical specifications to its energy use under specific weather conditions (Burman, Mumovic and Kimpian, 2014).

Currently, the EPCs are recognised as the best source of information about energy consumption in building stocks in many European countries (Volt *et al.*, 2020), however, doubts about how much credit should be given to methodologies highly relying on theoretical performance of buildings are rising (Kassam, 2017; Pritchard and Kelly, 2017; BBP, 2019).

1.1.3 Hotels

Hotels are among the commercial buildings affected by MEES. In general, hotel buildings are considered to be significantly energy intensive with high rates of CO_2 emissions (Navratil *et al.*, 2019). In the US, hotel buildings are among the top five energy consuming building categories (EIA, 2018). In other sources also, hotels are ranked fifth for energy consumption in the commercial buildings sector after food services, sales, health care and offices (Wang, 2012; Buso *et al.*, 2017). In the UK, hotels are one of the biggest energy consumers in the commercial buildings sector, after offices and retail buildings (Allouhi et al., 2015). Table 1.1 shows the share of hotel buildings in energy consumption of the commercial sectors.

Table 1.1 Energy consumption in commercial sector by building type (Allouhi *et al.,* 2015)

Building type	UK	Australia	USA
Offices	22%	25%	19%
Retail	17%	35%	23%
Hotels	16%	11%	7%
Education	10%	13%	11%
Hospitals	6%	14%	8%
Other	29%	2%	32%

The reasons for this high level of energy consumptions lie within the nature of hotels' services that require continuous heating/cooling, guests' expectations for high quality indoor environment and a constant need for domestic hot water (Deng and Burnett, 2000; Milojković, Nikolić and Stanković, 2012; Xing, Ren and Ling, 2015). Given the fact that most of the required energy is derived from fossil fuels, hotel industry's high CO_2 emission is not unexpected (Milojković, Nikolić and Stanković, 2012; Teng *et al.*, 2012). For example, in the UK's hospitality industry (accommodation and food services here), a share of 60% of annual energy consumption in 2018 was from fossil fuels, while the share of nuclear energy and other renewables were 30% and 10%, respectively (Ignite Economics, 2020).

Also, from a human behaviour point of view, guests might find themselves free of concerns about energy efficiency issues that they usually encounter in other places such as their own dwellings (Santamouris *et al.*, 1996; Roberts, 2008; Rotimi *et al.*, 2017). Although the energy intensiveness of hotels is known to those involved, tackling it is not always that straight forward. As the main goal of the hospitality industry is ensuring the highest level of comfort for guests (Taylor *et al.*, 2010; Milojković, Nikolić and Stanković, 2012), any measures for improving the energy performance of hotel buildings could only be considered if that utmost goal is not risked and the guests' quality of stay is not compromised.

While the global efforts aimed at reducing GHG emissions and tracking the building sectors energy performance are all valuable, it is equally important to keep a close eye on the actual effectiveness of these measures. Especially as the International Energy Agency (IEA) reports that despite all the measures, incentives and legislation, the building-related CO_2 emission in 2019 hit an all-time height of 10 gigatonnes (Gt) after flattening between 2013–2016 (IEA, 2020).

With these issues highlighted and review of the relevant literature, this research aims to take a critical look at the non-domestic EPCs in the context of hotel buildings, to address the potential drawbacks and shortcoming. Through this, under-researched aspects of non-domestic EPCs for hotels are studied, contributing to the existing knowledge on the effectiveness of MEES and EPC and their real contributions to reducing the GHG emissions beyond the theoretical assumptions on paper.

1.2 Knowledge gaps

Based on the initial review of the current literature, it was noted that although there are numerous studies about domestic EPCs in different countries, few studies, if any, are available where the main focus is non-domestic EPCs. While in the context of domestic EPCs, different topics are studied, ranging from effectiveness of EPCs and measures for improving them, to comparability of repetitive EPCs, the domain of non-domestic EPC has remained largely under-researched in many of those aspects. With this overarching gap, the findings of this study can contribute to the existing body of literature. With that highlighted, the following points have been identified for further research:

- Despite being in practice for more than a decade, it is unclear how the standard profiles and default assumptions for hotels' EPC stand up to the actual energy consumption patterns in hotel.
- With the growing emphasis on implementation of low/zero carbon technologies such as heat pumps, combined heat and power (CHP), the need for studies on the potential impacts of incorporating such technologies on hotels' EPCs is clear. This information is lacking currently.
- Currently, there are evidence from studies - mentioned in chapter 2 - suggesting that domestic EPCs struggle with reliability due to serious issues such as overestimation of space heating energy use. This has not been investigated about the non-domestic EPC in the UK. With the scheme being used for several years now, it seems the right time to take a deeper look on the matter and investigate the reliability of non-domestic EPCs.
- When it comes to hotel buildings, there is a large body of literature on how implementing different measures affects the energy consumption of hotels in different climatic situation. However, their impact on the EPC rating has not been a topic of investigation. Furthermore, there is definitely a knowledge gap in determining the key factors affecting the EPCs rating. This becomes even more important when considering that based on the MEES requirement, failing to meet the minimum levels can result in hefty fines and penalties.

1.3 Scope and significance of the research

1.3.1 Purpose of the research

With the MEES requirement legally in action, the commercial buildings sector has to either meet a minimum EPC rating or risk facing penalties. So, it will be important for the business owners – hoteliers here - to find out how they can comply with the requirements without compromising guests' comfort. This will be among the purposes of this research. But more importantly, it is now more than 10 years since the introduction of the non-domestic EPC in the UK and it is about the time to take a look on its contributions and reliability, as has been done extensively for the domestic EPCs.

Such schemes and policies tend to be very useful during the first few years - especially when there aren't any pre-existing measures in place - but as time goes on, issues begin to emerge and there might be the need for improvements and modifications. With the possibility of fines and penalties, it becomes even more important for the business owners and policy makers to make sure that the EPC scheme is reliable. Focusing on this aspect and investigating the potential sources of uncertainties is another purpose of this research.

Following on from the previous point, the importance of this research to industry is clear, but it's also worth emphasising its equal value in academic and research environment. The fundamental guidelines necessary to follow when generating non-domestic EPCs in the UK i.e., NCM guidelines - introduced fully in upcoming chapters - were all developed as a result of ongoing research at the Building Research Establishment (BRE). Academia has an important role to play in informing policy and ensuring climate measures perform effectively.

1.3.2 Research questions

With regards to the identified gaps in the knowledge, this work aims to answer the following questions:

1. With regards to the expected rise in temperature and the goal of attending to guests' comfort, what is the impact of adding cooling systems on a hotel's EPC rating?
2. Is there any source of controversy in the existing framework of the EPC for hotels?
3. Is there any source of uncertainty in the existing framework of the EPC for hotels?
4. Within the current framework of the non-domestic EPCs, what are the key factors in determining a hotel's EPC rating?
5. Can MEES effectively reduce the CO_2 emissions in the UK hotel buildings?

1.3.3 Research aims and objectives

As mentioned, the main goal of this thesis is to provide a deeper understanding of current non-domestic EPC within the framework of the MEES requirement and the context of hotel buildings through addressing the issues related to effectiveness of the scheme. In order to achieve this main goal, the following objectives are employed:

I. To model and simulate the thermal performance of four existing UK hotels by using a thermal analysis software which has the UK Government's approval for generating non-domestic EPC.

II. To investigate whether the results of an EPC calculation is comparable to the actual performance of the hotel.

III. To investigate whether the assumptions and standard profiles for hotels' EPC are realistic compared to the real conditions in hotels.

IV. To investigate the impact of the previous two objectives on identifying the key factors in calculating a hotel's EPC.

It is also important to mention while energy efficiency policies are all put forward with good intentions and in the hope that they can contribute to and enforce GHG mitigations, it is vital that they live up the principles behind them when it comes to effectiveness. This thesis is a first attempt to achieve a clearer picture of the UK's non-domestic EPC as the main character in the MEES policy.

1.3.4 Delimitation

Hotel buildings tend to be energy intensive due to an ongoing function which needs to provide heating/cooling and hot water almost 24/7. Also, unlike other types of commercial buildings, where the main purpose is usually limited to one activity e.g., dining or office tasks, hotels usually have to offer a wide variety of facilities and activities, from temporary accommodation to restaurants, gyms, and laundry facilities, with each of them having specific requirements in energy consumption and peak loads. Despite having these in common, the pattern of energy consumption can be very different from one hotel to another, based on the building's size, location - which affects the weather situation - level of services provided and even the age of the building. Therefore, a specific measure proved to be very useful in reducing the CO_2 emission and potentially improving the EPC rating for one hotel, may not necessarily be as useful to another. In order to make sure the results and findings of this research is applicable and accurate; a few points are elaborated below:

- As will be discussed fully in chapter 3, in this study, building modelling and simulation software is the main tool for studying the thermal performance of the hotels. The best models are those where the physical, operational and energy consumption aspects are as close to reality as possible. To achieve that goal and populate an accurate, reliable, and valid model, it is vital to have access to all the necessary data and information. In the case of hotel buildings, many of this information e.g. architectural drawings, heating, cooling and hot water systems' specification are considered confidential and not shared easily (Hui and Wan, 2013; Oluseyi, Babatunde and Babatunde, 2016). However, due to collaboration with Hilton, all of this information was provided. The benefit from close collaboration with Hilton proved especially helpful in comparing the standard profiles and simulation results with hotels' measured data (occupancy rates, microclimate, water, and energy consumption, etc.).

- The four cases studied in this research are selected as examples of typical UK hotel building stock in terms of size, building age and services:
    - **Example of purpose-built, new hotels with extra services such as swimming pool, designed and constructed in compliance with recent building regulations:** Hilton Reading, a new purpose-built hotel compliant with Building Regulation Part L 2006, with sealed fabric and full air conditioning system in place. Apart from the accommodation and event handling activities, the hotel has a large swimming pool and a high number of monthly food covers resulting in high level of energy consumption for catering activities. In-house laundry facilities are also available.
    - **Example of purpose-built hotels with older construction and lower levels of services:** Hilton Watford, a purpose-built hotel from 1970s without cooling systems in the guest rooms. The hotel provides the main services such as accommodation, evet handling and small restaurant, but extra services such as swimming pool and laundry services are <u>not</u> included.
    - **Example of a hospitality complex, combination of several buildings different in age and construction:** DoubleTree

Docklands, an example of a hotel complex where converted buildings from mid-19th century are operated along some purpose-built buildings from 1980s. Comfort cooling is provided in the building and the building fabric is not sealed.

- **Example of a high-end hotel in Scotland with several restaurants and application of low/zero carbon technology:** Edinburgh Hotel, an example of a hotel complex, comprising of two parts with the main building being a historic building (listed building) from early 1900s and the smaller section from 1980s. A mixture of services are provided in this building e.g., swimming pool, several different restaurants, and bars. A medium size CHP system serves parts of the building. The building fabric is not sealed and in fact, the historic building has still single layered glazing.

1.4 Structure and layout of the thesis

- **Chapter 1. General Introduction**

The current chapter presents a background to the research and states its significance. Furthermore, the identified gaps in knowledge, research aims, and research questions and the layout of the thesis are all presented in this chapter.

- **Chapter 2. Literature Review**

This chapter critically reviews the existing body of literature in the areas related to the scope and objectives of this research and starts by looking at the energy consumption in hotels and measures for improving their energy performance. The concepts behind forming and introducing the EPC in the EU comes next, followed by studies where similar energy labelling tools are looked at and the uncertainties involved in such schemes are discussed in detail with examples from different countries. The chapter continues to look at the studies focusing on the energy modelling and simulation tools and issues related to validations, especially in compliance modelling. Finally, measures suggested in the following chapters as means by which the EPC ratings of the studied hotels could be improved, are analysed in light of the existing body of literature

- **Chapter 3. Methodology**

This chapter discusses in detail the research philosophy, research design and strategy and specific means of data collection. Furthermore, as it is directly related to this study, the methodology and procedures behind calculating a non-domestic EPC (for England and Wales) is explained in this Chapter.

The research questions of this study can all be effectively addressed using a quantitative methodology. As it is common within the field of engineering, a computational fluid dynamic tool is used to model and predict the thermal performance and energy consumption hence CO_2 emission and EPC rating of the buildings. In this chapter, it is also discussed what measures are recommended by the literature for validating the simulation results and whether or not the results of EPC analysis can be "validated" using these measures.

As it is discussed in chapter 3, the estimated energy consumption for each hotel in its baseline situation - the actual/existing condition - is "compared" with the measured data. Depending on the specific objectives determined for that case, further simulations might be carried out.

- **Chapter 4. Improving the EPC rating of a complying hotel**

This chapter focuses on one of the four cases. It is acknowledged that the hotel is already complying with current requirements of MEES but in an attempt to see how the building responds to a potentially restricter policy, specific measures are tried to see the impacts on the EPC rating. These measures include thermally improved glazing elements (Low-*E* window films, Low-*E* coated, Argon-filled double-glazed units and triple glazing with double cover of Low-*E* and Argon-filled gaps), improved efficiency of heating/DHW system (replacing the gas-fired boilers with heat pumps and electric heater) and incorporating a CHP system. These measures are selected according to the building conditions, breakdown of energy end-uses calculated by EPC analysis and the growing recommendations for applying new technologies for reducing the CO_2 emissions, respectively. The main findings are presented through tables and graphs and discussed in full.

- **Chapter 5. Uncertainties surrounding the NCM assumptions for cooling end use in hotels**

This chapter focuses on the second case and investigates the impact of adding comfort cooling systems on the EPC rating of an existing hotel. The cooling systems are added to 180 guest rooms. The findings are surprising yet interesting and pave the way for a deeper look on the issue of usefulness of the current EPC calculations. The findings of this chapter can be especially important given the expected rise in temperature and the potential surge in installation of cooling systems in commercial buildings.

- **Chapter 6: Uncertainties involved in the current procedure of EPC generating in the UK**

This chapter compares the EPC ratings generated by the author of this research through EDSL TAS (introduced fully in chapter 3) with the commercial EPCs already available for each building by an independent assessor through another software (SBEM). A recurring discrepancy between the ratings by these two software - both accredited by the Government for the purpose - resulted in investigating and finding the reason behind this discrepancy. However, new issues emerged which needed further investigation using the measured data for occupancy rates, local weather conditions and water consumption. These steps resulted in finding another source of uncertainty in the current procedure of EPC for hotels, the impact of which can be significant for hotel owners and managers, especially those in challenge with the risk of non-compliance with MEES.

- **Chapter 7: Identifying key factors in determining the EPC rating**

This chapter is focused on finding the parameters with the highest impact on the EPC rating of a hotel. In order to achieve this objective, sensitivity analysis is used and carried out for three cases. The parameters to include in the sensitivity analysis are selected from those that are within the control of assessor and not those imposed by the standard profiles. In order to study the impact of each of these parameters, repeated rounds of simulation are carried out for each case in which only <u>one</u> parameter is changed at a time, which is how factors should change in a differential sensitivity analysis. Using statistical indicators, the parameters with highest impact on the EPC rating are identified. The findings of this chapter are useful in knowing which parameter to change if a significant improvement in the EPC rating is needed, for example for avoiding the non-compliance with MEES. Furthermore, the findings are also important for EPC assessors, knowing information about which parameter should be collected with more certainty. Comparing the findings of this chapter with those from chapter 6, brings up an important topic on the surface about the reliability of the EPC scheme.

- **Chapter 8: Scottish EPC**

This chapter examines a hotel in Scotland, for which the Scottish EPC is applicable. The building is examined through both Scottish and English EPC schemes. By discussing their similarities and their differences, it is explained why the ratings in a Scottish EPC should not be compared against a rating in English EPC. Measures for improving the EPC rating of the hotel and their impact is discussed in full details in this chapter.

- **Chapter 9: Conclusion**

In this chapter a summary of main findings - previously discussed at the end of each chapter - is provided. The implications of this research for both industry and research fields are discussed in more details. Furthermore, suggestions and ideas on further research are offered.

A note on the impact of Brexit on the EPC scheme

Although the EPC was part of an EU Directive, no specific change has been mentioned in terms of EPC uptake, especially as the UK has its own legislation for tackling climate change such as Climate Change Act and Building Regulations Part L. Furthermore, with its own ambitious energy and carbon targets, the UK government has already made it clear that high level of energy performance and emission reduction is expected from the building sector. For example, in response to the Committee on Climate Change‘s 2019 progress report, the UK Government suggests the minimum EPC rating for non-domestic buildings to be increased to band B by April 2030 (Climate Change Committee, 2020) compared to the existing MEES requirement of band E.

It is hoped that on the issue of energy, emissions and buildings, the UK and the EU continue to work together.

Chapter 2 Literature Review

In this chapter, existing literature related to the research questions and objectives are reviewed. The studies discussed in this chapter are related to the following topics:

- Energy consumption in hotels
- Energy performance certificate (EPC)
- Building energy modelling and simulation

Apart from these main three topics, studies about some of the measures that are applied for improving the EPC rating of the hotels are reviewed at the end of this chapter.

2.1 Energy consumption in hotel buildings

2.1.1 Key parameters affecting the hotels' energy consumption

International and national research into hotel industry's energy consumption has been a hot topic since 1990 (Pieri, IoannisTzouvadakis and Santamouris, 2015) resulting in a large body of literature concerning the energy consumption and energy performance retrofitting measures in hotels. A summary of some of these studies is presented in the following paragraphs.

Bohdanowicz and Martinac (2007) divided the factors affecting the energy consumption of a hotel into two main groups of physical and operational parameters. Weather conditions, building fabric specification and the building's age are among the most important physical parameters while level of facilities provided e.g., having swimming pools and laundry and also guests' preferences for indoor environment are among the influencing operational parameters. In an earlier study on 16 hotels in Ottawa, Zmeureanu *et al.* (1994) used a weather normalisation method and broke down the factors affecting the total energy consumption into weather-dependant and weather-independent parameters. According to Díaz Pérez *et al.* (2019) the energy consumption of a particular hotel depends on its geographical location, facilities and the categories of the establishments. In their study on the hotels in Sweden and Norway, Smitt *et al.* (2021) found an inverse relationship between hotel size and energy consumption. Their explanation pointed to the typical energy systems installed in different size hotels: smaller hotels are often located in city centres, therefore, the financial benefits from replacing the outdated thermal systems are usually limited by space, building mass and investment cost issues. On the other hand, large hotels have considerable amounts of energy consumption hence significant operational costs, therefore, chances of installing highly efficient energy systems are higher in these hotels, as the potential savings are considerable alongside shorter payback time (Smitt *et al.*, 2021).

It has been mentioned by several studies that the weather conditions and climatic situations affect the energy consumption (Milojković, Nikolić and Stanković, 2012; Cabello Eras *et al.*, 2016). The literature suggests that in both hot and cold climate the energy consumption is higher (Deng and Burnett, 2000; Bohdanowicz and Martinac, 2007; Priyadarsini, Xuchao and Eang, 2009) compared to the milder climate (Rosselló-Batle *et al.*, 2010). In the study by Deng and Burnett (2000) on 16 hotels in Hong Kong, the researchers found that the monthly electricity consumptions of the hotels are highly correlated with the monthly mean external temperature, whereas it was not directly affected by the monthly number of guests. The same finding was appraised by Hui and Wan (2013) and Pablo-Romero, Pozo-Barajas and Sánchez-Rivas (2019). The latter study also found that during the colder times – lower temperatures – due to higher heating loads, the electricity consumption is increased again.

Findings from other studies suggest that hotels located in the areas with hot summers and cold winters tend to have higher energy consumption than those in cold area or those in areas with hot summer and warm winters (Sheng *et al.*, 2018; Wang, Meng and Zhang, 2021). In another study carried out on 45 hotels in Shanghai by Yao, Zhuang and Gu (2015), the researchers found that in general, hotels' energy consumption follows the outdoor temperature's variations, either positively (April to November) or negatively from December to March.

In a study on 29 hotels in Singapore it was claimed that staff density and the number of years passed since the latest major retrofit in the building can impact the energy consumption. The study used the Energy Use Intensity (EUI) as an indicator which is the energy consumed in the hotel divided by the unit of gross floor area. The study suggests that the correlation between EUI and the number of staff can be partly explained by the fact that a greater number of staff is an indication of higher levels of activities running in the hotel (Priyadarsini, Xuchao and Eang, 2009). In another study on 200 Taiwanese hotels with different rates - from international hotels to bed and breakfast facilities - Wang (2012) found that gross floor area is the element with second highest correlation factor for total energy consumption and EUI. Whereas the first element for each of those dependent variables are number of rooms and yearly occupancy rates, respectively. Table 2.1 provides a summary and some further information on the studies discussed in preceding paragraphs.

Table 2.1 List of studies on hotels energy consumption and their findings

Study	Location/ No of cases	Parameter(s) studied in relation to energy consumption	Metric for energy use
Deng and Burnett (2000)	16 hotels in Hong Kong	Year of construction, class of hotel, total gross floor area, occupancy rates	kWh/m²
Bohdanowicz and Martinac (2007)	184 international hotels in Europe	Climatic conditions, building size, occurrence of major servicing needs, number of guest-nights and food-covers	kWh/m²
Priyadarsini, Xuchao and Eang (2009)	29 hotels in Singapore	Worker density, years after the last major energy retrofit, number of occupied rooms	kWh/m²
Milojković, Nikolić and Stanković (2012)	NA	Number of rooms in a hotel	NA
Wang (2012)	200 hotels in Taiwan	Gross floor area, number of rooms and annual occupancy rates	kWh/m²
Cabello Eras *et al.* (2016)	2 hotels in Cuba	Outdoor temperature	MWh/RDD (RDD: room degree day)
Sheng *et al.* (2018)	310 hotels in China	Climatic conditions during winter and summer	kWh/m²
Pablo-Romero, Pozo-Barajas and Sánchez-Rivas (2019)	Hotels in Spanish Mediterranean provinces (no number mentioned)	The impact of cooling degree day (CDD) and heating degree day (HDD)	NA
Smitt *et al.* (2021)	140 hotels in Sweden and Norway	Hotel size	kWh/m²

While some studies mention the impact of occupancy rates on hotel energy consumption (Panayiota Pieri, Tzouvadakis and Santamouris, 2015), some other studies report inability to find a meaningful correlation between occupancy rates and hotel energy consumption (Lai, 2016). This is partly explained by the fact that for avoiding unpleasant odours, the air conditioning systems will be kept on even when the guest rooms are not occupied/booked (Deng and Burnett, 2000). Additionally, some studies suggest that the impact of occupancy rates on energy consumptions start to appear when the occupancy drops below 70% (Commonwealth of Australia, 2002; Priyadarsini, Xuchao and Eang, 2009).

As pointed out in chapter 1, some studies suggest that people tend to hold a less cautious approach towards energy consumption when staying in hotels (Santamouris *et al.*, 1996; Roberts, 2008; Rotimi *et al.*, 2017). On the other hand, some studies claim that in recent years, guests have become more aware of environmental issues (Cingoski and Petrevska, 2018) and tend to show more flexibility towards saving energy (Han et al., 2011; Buso *et al.*, 2017) and even preferring the hotels with better energy performance when deciding where to stay (Panayiota Pieri, Tzouvadakis and Santamouris, 2015). Some studies even suggest that by applying more environment-friendly approaches, hotels leave a positive impact on their guests resulting in higher customer satisfaction and higher chances of a revisit (Lee *et al.*, 2010; Kularatne *et al.*, 2019).

In terms of energy carrier, studies suggest that among different types of fuels used in hotels, the share of electricity is increasing significantly. Furthermore, it accounts for the highest share in energy costs (Milojković, Nikolić and Stanković, 2012; Hui and Wan, 2013; Cabello Eras et al., 2016). This is due to the role of electricity in powering so many different services in hotels such as heating, ventilation and air conditioning (HVAC) systems, lighting, lifts operating and laundry systems and sometimes water heating - when electrical heaters are used (Priyadarsini, Xuchao and Eang, 2009).

2.1.2 Energy benchmarking in hotels

During the practice of evaluating the energy efficiency of a building, its energy performance is usually compared with that of similar buildings. This practice is known as *energy benchmarking* (Pérez-Lombard *et al.*, 2009; Chung, 2011; Nikolaou, Kolokotsa and Stavrakakis, 2011). This comparison can be done either through some specific properties such as thermal specifications, e.g. building elements' U-values, or through buildings' overall energy consumption or energy sue for different end-uses, e.g. space heating and cooling, etc. (Borgstein, Lamberts and Hensen, 2016).

The use of this word i.e., benchmarking, was originally exclusive to topography, and it referred to a reference point in terrain for geological analysis. In 1970s, in an attempt to compare the key production factors and monitoring the improvements, some companies came up with the idea of benchmarking tools. Later on in 1990s, the term building energy benchmarking emerged as the efforts for comparing the energy consumption of buildings from similar categories started (Pérez-Lombard *et al.*, 2009).

In a more elaborate definition, building energy benchmarking includes not only the act of comparison but also the ongoing practice of monitoring and reviewing a building's energy consumption with the purpose of determining whether it is improving or not. The building's energy consumption can be compared to its own performance i.e. through historical data or other buildings of the similar type (Government of Canada, 2020). Through energy benchmarking the energy consumption of similar buildings are compared, future targets can be set and measures for improving the energy efficiency can be determined (CIBSE, 2012). Nowadays, energy benchmarking has become a key management tool for performance measurement and improvement and there are three general approaches to it, shown in Table 2.2.

Table 2.2 General approaches to energy benchmarking (Hui and Wong, 2010).

Approach	**Description**
Tracking or baseline approach	Comparing a building to itself
Target finder approach	Empirical model from a sample of other similar buildings in a population
Simulation model approach	Results of an energy simulation model with certain predefined baseline characteristics, such as meeting an energy code or standard

Energy benchmarks for hotels are usually based on their type. Therefore, the benchmarks for luxury, business/holiday and small hotels are usually different (CIBSE, 2012). The energy benchmarks in hotels are often expressed in energy consumed per gross floor area (EUI) or the number of guest rooms:

- Hotel's energy consumption per floor area (kWh/m^2) per year
- Hotel's energy consumption per guest room per year
- Hotel's energy consumption per guest night (Hui and Wong, 2010)

Since 1990s, in an attempt to find the energy consumption benchmarks for a group of hotels, average annual energy consumption of hotels has been studied around the world. Some of these studies and their findings are demonstrated in Table 2.3.

Table 2.3 Average energy consumption for hotels

Study	**Location**	**Number of cases**	**Average energy consumption (kWh/m^2)**
Zmeureanu *et al.* (1994)	Canada	16	612
Santamouris *et al.* (1996)	Greece	158	273
EIA (1995)	US	NA	401
Deng and Burnett (2000)	Hong Kong	16	564
Cardona and Culotta (2001)	Italy Portugal	NA	364.4 296.4
Commonwealth of Australia (2002)	Australia	50	Accommodation 208.3 Business 291.6
Deng (2003)	Hong Kong	36	542
CIBSE (2004)	UK	NA	Small 480 Holiday 540 Luxury 610
Önüt and Soner (2006)	Turkey	32	425.36
Priyadarsini, Xuchao and Eang (2009)	Singapore	29	427
Wang (2012)	Taiwan	19 45	Standard 237.7 International 280.1
Yao, Zhuang and Gu (2015)	Shanghai	45 in total	3-star 215.7 4-star 234.8 5-star 279.8
Smitt *et al.* (2021)	Sweden and Norway	140 in total	213

As illustrated in Table 2.3, not only the average energy consumption fluctuates from one country to another, but also different regions within the same country can have very different energy consumption levels due to different climatic situation and operational characteristics of the hotels (Pieri, IoannisTzouvadakis and Santamouris, 2015).

Different countries around the world use different tools and indicators for energy benchmarking. In the U.S., the Energy Star portfolio is the widely used platform for this purpose. In the UK, the Energy Efficiency Best Practice Programme (EEBPP), established in 1989, used to produce energy benchmarking for different types of buildings. According to its Guide 36, there were two indicators for hotels' energy benchmarking based on their type: energy consumption per unit of area (kWh/m^2) and fuel (gas/electricity) costs per bedroom. Based on these indicators, the hotels performance would be described as good, fair, or poor (BRECSU, 1993). In 2002, the responsibilities of EEBPP were transferred to other corporations and currently other tools like the one provided by Carbon Trust (2020) can be used for hotels energy benchmarking.

While traditionally the EUI has been recognised as a benchmark for hotels' energy consumption, some studies suggest that due to the variety of factors involved, the EUI cannot be a meaningful measure anymore (Karagiorgas, Tsoutsos and Moiá-Pol, 2007; Hui and Wan, 2013; Teng, Wu and Xu, 2017) and they have called for development of new energy performance indices. According to these studies, a hotel's energy consumption is affected by many technical, physical, operational, and even managerial factors while the EUI is too simplistic, taking into consideration only a single parameter i.e. floor area and ignoring underlying issues in individual energy end uses (Hui and Wong, 2010; Hui and Wan, 2013). In an attempt to come up with new energy indicator for hotels in Hong Kong, Hui and Wan (2013) used a mathematical programming model called Data Envelopment Analysis. The model was implemented on series of observational data to form new estimation of relations between elements and was first put forward by Charnes, Cooper and Rhodes in 1978. The input data used in the study were electricity, gas and water use, outdoor temperature, and relative humidity to investigate the corelation to outputs of number of room nights, number of room guests and the food and beverage covers. Similarly, Teng, Wu and Xu (2017) suggested using a composite indicator for energy consumption which takes into account the hotel's characteristic including both the energy use characteristics and operating income characteristics. However, the suggested new indicator can only be used in limited services hotels, equivalent to two/three stars.

Despite the criticisms it has received, some researchers still support using the EUI. For instance, Sheng *et al.* (2018) stated that due to the normalised nature of this index, it can be expected from the EUI to provide a comparative basis for energy use in different hotels and its application can be beneficial for carrying out statistical analyses. Furthermore, Choudhary (2012) is of the opinion that EUI is an acceptable standard normalisation when it comes to scaling up the energy consumption of a large sample of similar buildings into gross energy use of a district. Furthermore, it is suggested by some researchers that although the EUI might involve some standardisations that do not cover the building construction and/or physical characteristics, it should still be considered a legitimate index within the non-domestic buildings where differences in energy consumption of two buildings is mostly due to differences in demand for activity related services.

2.1.3 Energy efficiency measures in hotels

The structure of energy consumption in a hotel can be very complicated and even difficult to understand and control (Udawatta, Perera and Witharana, 2010). This is partly due to the specific requirements of energy management in hotels, stemming from continuous operating, the need for different services through distinct departments and guests different expectations (Milojković, Nikolić and Stanković, 2012).

In order to come up with useful and practical ideas to improve the energy efficiency of a hotel, it is strongly suggested that a comprehensive energy audit needs to be carried out to identify the major points of inefficiencies (Santamouris *et al.*, 1996; Beccali *et al.*, 2009; Hotel Energy Solutions, 2011; Cabello Eras *et al.*, 2016). However, pinpointing the shortcomings may not always be a straight forward task as many hotels tend to only monitor their overall energy consumption, without detailing the energy consumption for different end uses (Gössling, Scott and Hall, 2015; Ivanko, Sørensen and Nord, 2021). This is partly due to the expensiveness of the technology needed for separately monitoring the energy consumption by each end-use (Priyadarsini, Xuchao and Eang, 2009). Also, lack of necessary technical awareness among the hotel staff contributes to hesitation among the hoteliers in introducing new energy management tools and technologies (Coles and Zschiegner, 2011; Coles, Dinan and Warren, 2014). In most cases, the energy meters installed in hotels monitor the consumption based on the type of energy carrier, for instance, electricity, and natural gas.

After the energy audit, the next step is to investigate the suitable measures, as the literature suggests that the choice of energy retrofit measures should be made based on the size, facilities and local climate (Chen, Ji and Xu, 2012). A study on cost effective measures for improving the energy efficiency of hotels in Nepal found that a given measure proved to be successful in reducing the energy consumption of a hotel in a specific climatic zone can be absolutely useless for another building in a different climatic situation (Bodach, Lang and Auer, 2016). Given the importance of generalisability of research findings, it should be mentioned that while it is highly possible that hotels with similar situations – similar size, exposure to the outdoor weather, typed of services - benefit from similar energy retrofitting measure, the final choice should be based on precise study and calculation for each individual case. In a study done by Salem and colleagues (2018), the researchers found that despite being helpful in reducing the energy consumption and CO_2 emission of an existing UK hotel under current weather data, the same measure may be ineffective in reducing the CO_2 emissions under the future weather data.

Availability of technologies and cost effectiveness are among the important factors when it comes to choosing the measures for reducing the energy consumption of hotels. In the large-scale study by Bianco and colleagues (2017), the researchers developed an energy model of Italian hotel sector and investigated the impact of two different scenarios, i.e. best available technology (BAT) and realistic scenario on the primary energy consumption and GHG emission of the sector. The study found that while high theoretical energy savings can be achieved through BAT, the financial sustainability becomes an issue. For realistic scenario, the achievements are the opposite (Bianco *et al.*, 2017).

The measures for improving the energy efficiency of a hotel building can be classified in three main groups:

I. **Energy management:** focusing on hotel's energy efficiency strategies with energy conservation and staff/guests' cooperation in perspective.

II. **Reducing the cooling and heating demand of the building:** focusing on protecting the building from extreme cold or heat.

III. **Equipment efficiency:** focusing on improving the building's systems through replacing the old/inefficient systems or improving the system operation (Hotel Energy Solutions, 2011).

2.2 Energy Performance Certificate

2.2.1 Background

2.2.1.1 Origins of building energy performance in Europe

Worldwide energy crises in 1970s, caused by problems in the Middle East - such as the Arab countries' embargo in 1973 boycotting the west, and Iran's revolution in 1979 - raised concerns among the European countries over the safe and secure supply and access to energy resources, especially among those highly dependent on the oil from politically unstable areas. Combined with the increasing role of building sector in global energy consumption, it resulted in a new concept being introduced in the field of energy efficiency in buildings. The concept was energy certification for buildings (Pérez-Lombard *et al.*, 2009). One of the earliest mentions of buildings energy certificate occurred in the European Council Directive 93/76/CEE, where energy certification of buildings was declared fundamental for limiting the CO_2 emissions through energy efficiency. According to the Directive's Article 2, energy certification of buildings "*shall consist of a description of their energy characteristics, must provide information for prospective users concerning a building's energy efficiency. Whereas appropriate, certification may also include options for the improvement of these energy characteristics*" (Council Directive, 1993, p. L 237/29). This directive was non-binding, and it was rather ambiguous, which resulted in low implementation among the Member States. As the time passed, the EU acknowledged the need for a more powerful, enforcing instrument for the Member States. Therefore, in 2002, the Energy Performance Building Directive 2002/91/EC was introduced, calling on Member States to encourage higher levels of energy performance in their countries' building sector by setting new standards and guidelines, evaluating the buildings' performance on a consistent basis and, effectively communicating the buildings' energy performance through a standard certification system (DCLG, 2015).

2.2.1.2 Requirements of the EPBD

The Directive includes several Articles, those related to the topic of this work are:

- **Article 2:** definitions related to the purpose of the Directive
- **Article 3:** adoption of a methodology for calculating the integrated energy performance of buildings, to be applied at a national or regional level. This article also suggests that the energy performance of a building can be expressed through a CO_2 emission indicator.
- **Article 4:** setting minimum energy performance requirement for new and existing buildings.
- **Article 5:** ensuring that the requirements for energy are met in new buildings
- **Article 6:** ensuring that the requirements for energy performance are met in existing buildings after undergoing major changes.
- **Article 7:** developing energy certification of buildings (EPBD, 2002)

Article 2 of the EPBD defines the energy performance of a building as the estimated amount of energy needed for the <u>standardised use</u> of the building. This emphasis on the standardised condition is so that the comparison between the buildings from the same category are based on their intrinsic properties rather than being dependant on how the systems are used (DCLG, 2015). Furthermore, standardised conditions make it easier for the regulators and enforcing bodies to compare the energy performance of buildings from similar categories (Burman, Mumovic and Kimpian, 2014).

As stated above, Article 3 of the EPBD requires the Member States to develop a methodology for calculating the energy performance of their building sector. According to an annex to the Directive, the calculation should be based on a general framework, at least covering the following factors:

- Thermal specification of the building fabric and internal partitions.
- Space heating and domestic hot water systems specification

- Cooling system and/or air conditioning installations
- Natural and mechanical ventilation
- Built-in lighting system
- Orientation of the building and the weather it is exposed to
- Passive solar systems and protection from sun
- Indoor climatic conditions

Furthermore, where relevant, the influence from renewable source of energy, the electricity generated by combined heat and power and natural lighting on the building energy performance should be considered (EPBD, 2002; DCLG, 2015).

2.2.2 UK's response to EPBD requirements

2.2.2.1 National Calculation Methodology (NCM)

The UK's response to the call for a calculation methodology on the energy performance of the building sector was established by the Office of the Deputy Prime Minister - now the Department for Communities and Local Government (DCLG). The response was to state in the 2006 Building Regulation Part L for England and Wales:

"*17A - (1) The Secretary of State shall approve a methodology of calculation of the energy performance of buildings.*

(2) The methodology shall comply with the requirements of the Directive.

17B - The Secretary of State shall approve minimum energy performance requirements for new buildings in the form of CO_2 emission rates, which shall be based upon the methodology approved pursuant to regulation 17A." (DCLG, 2015, p. 12). The National Calculation Methodology (NCM) was then developed to carry out the calculations.

The reasons for preferring CO_2 emission over energy consumption as an indicator for a building's energy performance are to:

- Allow comparison of energy use from different sources and costs
- Avoid misunderstanding over primary and delivered energy
- Remind users that the ultimate goal behind these calculations and the need for compliance is to cooperate in international efforts for carbon management (DCLG, 2015).

2.2.2.2 Building Regulation compliance

A fundamental part of the NCM which is in response to Article 4 of the EPBD 2002/91/EC, is that the energy performance of a building is calculated based on comparing its estimated annual CO_2 emission with a target. To this end, the proposed/actual building's CO_2 emission is compared with and the emission rate of a notional building, i.e., Target Emission Rate (TER). The performance requirement is that the proposed/actual building's emission rate (BER) should be less than TER.

The Notional building has the same size, shape, and zoning arrangements as the Actual building. Any specification assigned to the Actual building in terms of building orientations, type of activity in the zones, exposure to outdoor weather and the type of building services, will also be applied to the Notional building, however, in terms of the building fabric elements' U-values, access to natural light through glazing and efficiency of the systems, the Notional building has to follow specific guidelines, regardless of the situation in the Actual building (DCLG, 2013). Full details about Notional building's specification are provided in NCM Modelling Guide (DCLG, 2013), Building Regulations Approved Document Part L 2010 - latest update in December 2021 (HM Government, 2014) and Non-domestic Buildings Services Compliance Guide (HM Government, 2013).

After checking that the BER does not exceed the TER (through one of the approved software tools, discussed in chapter 3, section 3.2.4), other checks are also carried out in parallel to investigate further compliance. The criteria for checking compliance are:

- Criterion 1: The calculated CO_2 emission rate for the building must not exceed the target (i.e., BER < TER)
- Criterion 2: The performance of the building fabric and fixed building services should achieve reasonable overall standards of energy efficiency.
- Criterion 3: The spaces in the building should have appropriate passive control measures to limit solar gains.
- Criterion 4: The performance of the building, as built, should be consistent with the calculated BER.

- Criterion 5: The necessary provisions for enabling energy efficient operation of the building should be in place.

2.2.2.3 Asset rating

Article 7 of the EPBD 2002/91/EC calls for developing a certification system for effective communication of a building's energy performance. The certificate should be issued after the completion of the construction work or when the building is sold or rented. Similar to what was defined as the energy performance of a building in Article 2 of the Directive, the certificate should demonstrate *"the intrinsic, as-built energy performance based on standardised operation patterns and internal conditions for the mix of activities taking place in the building*" (DCLG, 2015, p. 113). The UK's response to this requirement is called asset rating, which is presented through the Energy Performance Certificate (EPC). Through the EPC, the relative energy performance of a building is expressed in layman's term. The term "relative" is used as the rating enables the buildings with similar uses - according to the EPBD, the buildings should be classified in different categories based on their use - to be compared on an equal basis for their potential to be operated efficiently without considering the users' choices on how to operate the systems (DCLG, 2013, 2015).

As explained in section 2.2.2.2, for Building Regulation compliance, the standardised emission from the proposed/actual building is compared with that of a Notional building. For the asset rating, the comparison is between the standardised emission of the actual building, i.e., BER and that of a "reference building". As this is directly related to this work, the definition of the reference building and the process behind calculating the asset rating is discussed in detail in chapter 3, section 3.2.

The formal EPC should be issued by an accredited assessor using one of the approved software tools (see chapter 3, section 3.2.4) and lodged into a central database. According to Energy Performance of Buildings Certificates statistical release which updates the data quarterly, from 2008 to the end of September 2021, more than 22 million EPCs have been lodged in England and Wales, 95% of which are for domestic EPCs (MHCLG, 2021), Table 2.4. According to the numbers provided in the same document, the total number of EPC lodgements in 2020 were reduced compared to 2019 by around 7.3% which could be due to the impact of the Covid 19.

Table 2.4 EPC lodgements in England and Wales from 2008 to September 2021 (MHCLG, 2021)

Type of EPCs	Number of lodgements	Percentage of total
Domestic	21,858,105	95.6%
Non-domestic	1,012,368	4.4%

A note on the impact of Covid-19 pandemic on the UK's emission rates

According to the report by Climate Change Committee (2021), following the restrictions from the Covid-19 pandemic, the UK saw a record decrease in its total emission by around 13%, with the vast majority of fall - more than 70% - coming from reductions in transport emission. Emissions from non-residential buildings were reduced by 8% compared to 2019. As people spent more time in their houses due to lockdown, the residential buildings emission was increased by 2%, the only sector to show an overall increase of 2% in emissions.

The reduction in emission in 2020, will have no practical impact on the UK's contribution to global warming, mostly because the fall in sectoral emissions is temporary, as they do not reflect any structural change in their respective underlying systems (Climate Change Committee, 2021).

2.2.3 Response from other countries and the EPBD recast

According to EPBD 2002/91/EC, the proposed certificate scheme should be applied to the following buildings:

- All buildings or building units which are newly constructed or undergo major renovation
- All buildings or building units sold or rented out to a new tenant
- All buildings where a total useful floor area over 1,000 m^2 is occupied by a public authority and frequently visited by the public (Arcipowska *et al.*, 2014).

Despite all the requirements and high expectations, the EPBD 2002 did not provide any details on the methodology, leaving it totally to the Member States to develop a certification system for informing the energy performance of their building stock. Member States came up with different calculation methodologies, most of which relied on whole building thermal simulations (Intelligent Energy Europe, 2008; Burman, Mumovic and Kimpian, 2014). Although in a few countries such as Netherlands and Denmark, there were already energy performance certification schemes in place, but for most of the Member States, the whole idea was new and needed to be developed from the very beginning (Arcipowska *et al.*, 2014).

EPBD Recast (2010) (Directive 2010/31/EU) introduced further requirements with the purpose of increasing the role and quality of the EPC. For instance, the Member States were asked to state the EPC rating in any advertisement placed on the market for the property, whether it was for rent or sale and the new buyer or tenant should have easy access to the EPC rating (Li *et al.*, 2019). During the years, expectations from EPCs became higher, for instance, the floor area for buildings eligible to apply for an EPC went down from 1000 m^2 to 500 m^2 in 2002 and then 250 m^2 in further recasts (Arcipowska *et al.*, 2014). Figure 2.1 provides a chronological illustration of EPBDs related to EPC.

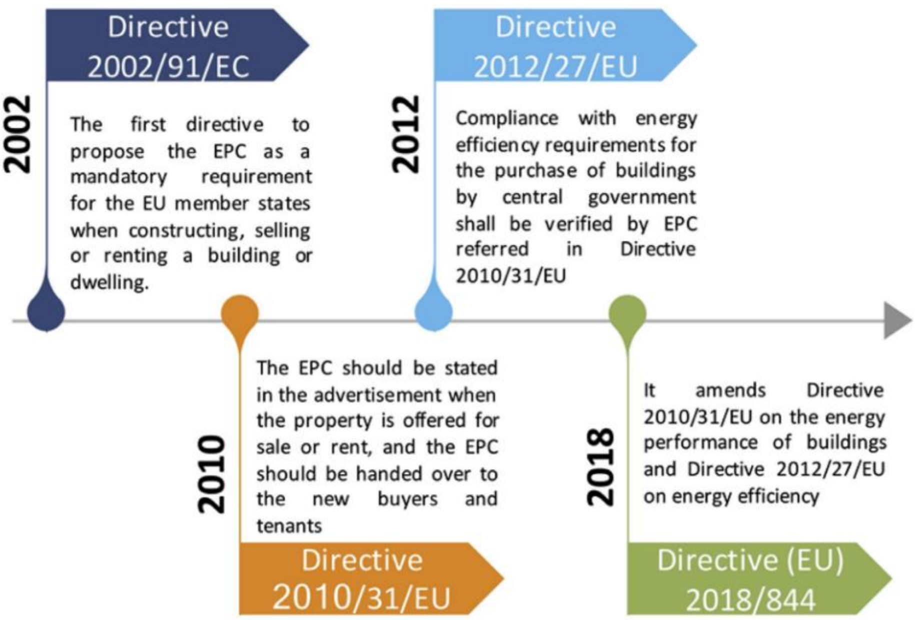


Figure 2.1 Timeline for EPBD Directive related to EPC (Li *et al.*, 2019)

By 2015, all the Member States had formally incorporated the EPC scheme in their national legislations. Currently, the statistics show that the UK has the highest number of EPC uptakes with more than 20 million issued and registered EPCs (Volt *et al.*, 2020). Currently, the EPCs are known to be one of the most informative tools on energy performance of buildings in EU (BPIE, 2011; Arcipowska *et al.*, 2014; Sutherland *et al.*, 2016; Sesana and Salvalai, 2018).

As mentioned, the decision on the methodology for buildings' energy performance and the certificate system for effective communication of this performance was fully left to the Member States. As pointed out in chapter 1, most of the Member States opted for whole building thermal analysis, using thermal modelling and energy simulation tools (Intelligent Energy Europe, 2008). As the EPBD suggested either calculated or actual (measured/operational) energy consumption can be used (Semple and Jenkins, 2020), almost half of the members opted for methodologies that exclusively based on calculated energy consumption. Some of the members agreed on using both operational and calculated energy consumptions (Morsink-Georgali and Fokaides, 2020). Table 2.5 compares the EPC schemes in some of these countries.

Table 2.5 Specification of EPC schemes in some countries (Atanasiu and Constantinescu, 2011)

	Implementation	**Assessment**	**Performance indicator**
Austria	National and regional	Calculated rating	kWh/m^2 per annum
Belgium	Regional	Calculated and measured rating	kWh/m^2 per annum
Czechia	National	Calculated rating	GJ per year
Denmark	National	Calculated rating	No specific information
France	National	Calculated and measured rating	kWh/m^2 per annum
Germany	National	Calculated and measured rating	kWh/m^2 per annum
Hungary	National	Calculated and measured rating	No specific information
Ireland	National	Calculated rating	kWh/m^2 per annum and CO_2 emission
Netherlands	National	Calculated rating	Energy index
Poland	National	Calculated rating	No specific information
Portugal	National	Calculated rating	kWh/m^2 per annum
Spain	National and regional	Calculated rating	No specific information
United Kingdom	National and regional	Calculated rating	kWh/m^2 per annum and CO_2 emission

Despite similarities and common concepts behind them (Hardy and Glew, 2019), there are different regimes of EPCs implemented among different countries (Tigchelaar, Daniels and Menkveld, 2011; Amecke, 2012; Murphy, 2014; Abela *et al.*, 2016; Jenkins, Simpson and Peacock, 2017), therefore the comparability among EPCs from different countries are low. Despite the inevitable variation of EPC schemes around the EU (Majcen, Itard and Visscher, 2013), studies suggest that since the EPBD Recast in 2010, the market for energy renovation and retrofitting has experienced a considerable growth (Menicou *et al.*, 2015; Charalambides *et al.*, 2019).

2.2.4 EPCs as energy labelling, market-signalling, and policy tools

With the EPCs becoming part of national legislation in different countries, their roles in providing energy performance information to building owners, occupants and those active in real estates have grown considerably (Atanasiu and Constantinescu, 2011; Sesana and Salvalai, 2018). In a research on EPC schemes, Arcipowska and colleagues (2014) investigated different national approaches on generating and registration activities carried out around the EU. According to this study, the EPC can be considered both an information and marketing tool for different stakeholders in real estate sector (Arcipowska *et al.*, 2014). Volt and colleagues (2020) are of the idea that the EPCs are the best source of information about energy consumption in the EU's building stock.

Apart from their role in informing the owner and/or the user about the energy efficiency of the building, some researchers have been optimistic about the role of EPCs in creating a demand for buildings with better energy performance in the market, as they allow the owner/user to estimate the potential energy bills (Atanasiu and Constantinescu, 2011; Sesana and Salvalai, 2018). With regards to the role of EPC in sending market signals, some studies suggest that there might be a correlation between the EPC rating and the price of a property. One of these studies investigated more than 330,000 domestic EPCs in the UK and verified the existence of a positive correlation between the two (Fuerst *et al.*, 2015). In order to eliminate the effect of the size of the property, the dependant variable was expressed as price per square meter area of the dwelling. In Italy, Tronchin and Fabbri (2012) found that the EPC rating can change the inclination of the buyers in the dwelling market and orientate their preferences in choosing the property. Contrary to these findings, a study on Dutch dwelling showed that the EPC rating had a weak influence, if any, on the purchase of the property (Murphy, 2014). The same study also mentions that although energy efficient properties (dwelling) are respected and valued by the owners, but usually the most influential factors in choosing a dwelling are location, size, and price. According to the study by Amecke (2012), EPCs can have a minor impact on the market value of domestic properties in Germany, as it is difficult to draw any conclusion from the EPC rating on the energy costs of the dwelling. The study also claims that legal restrictions on accessibility of EPCs - as opposed to the open access policy in the UK - could have also played a negative role. In a study in Denmark, 58% of people who purchased a property in 2015, stated that the EPC had an impact on their choice of property, while 18% indicated that the EPC rating did not matter at all when purchasing the property (Volt *et al.*, 2020).

In the study by Toleikyte and colleagues (2016) in eight different European countries including Austria, Norway, France and Italy, the energy cost factor - represented through the EPC rating - received 10th place on the list of property selection factors, with those found in the study by Murphy (2014) i.e. location, price and size dominating the list. In line with these studies, Charalambides *et al.* (2019) found that not only is the role of EPC limited in decision making for purchasing and renting a property, but its impact on energy renovation is not considerable either. This study was based on an online survey carried out in 12 countries. There are also evidences from the works of Bartiaux *et al.* (2011), Watts, Jentsch and James (2011) and Christensen *et al.* (2014) that among those active in real states, many simply see the EPC as a waste of money without leading to any actual improvement in the building stock. Based on these studies, it seems the EPC rating is far from being a highly influential parameter when it comes to deciding on purchasing a dwelling.

Outside of the dwelling stock, Fuerst and McAllister (2011) investigated 708 commercial properties - retail, office, and industrial buildings - in the UK. The study could not find any impact from the EPC rating on the rental and capital values. The study concludes that the reason behind the lack of a meaningful link between EPC rating and the pricing in commercial building sector can be partly explained by the fact that in commercial sector the occupants are usually tenants rather than being the owners. The EPC ratings are either kept from them or are of little interest to them (Fuerst and McAllister, 2011). Similarly, studies by Bonde and Song (2013) in Sweden and Surmann, Brunauer and Bienert (2015) in Germany could not find any impact from the EPC rating on the market value of commercial (office) buildings. The findings of the study by Nappi-Choulet and Décamps (2013) on capitalization of EPCs on corporate real estate values are different to those mentioned earlier, as this study found a positive impact from energy certificates on rental prices, however, the study confirms that this impact also depends on the type of commercial building. The impact on the sale values was not as significant, regardless of the building type. In a study by Parkinson *et al.* (2013), occupants responses to a survey about satisfaction with their workplaces were matched with their corresponding offices' EPC rating and rental values. Interestingly, the study found a correlation between the EPC rating and facility services, such as facility aesthetics. The authors concluded that within the framework of their research, the EPC could be a valid indicator of occupants satisfaction with their corresponding offices; energy performance and overall facility satisfaction (Parkinson *et al.*, 2013). Overall, it seems that empirical evidences for positive impacts from EPCs on property values are inconclusive and at times, contrary as suggested by Olaussen, Oust and Solstad (2017).

2.2.5 The reliability issues and uncertainties emerging in the EPC schemes

According to Ahern and Norton (2020), all the national EPCs should show the following characteristic:

- Accuracy and reliability, meaning that for a given climate, buildings which hold a more efficient rating, happen to actually demonstrate lower level of energy consumption (Stein and Meier, 2000; Pérez-Lombard *et al.*, 2009; Sousa *et al.*, 2017)
- Showing capacity to be applied to a wide range of buildings rather being specific to one type of building (Arkesteijn and Dijk, 2010; Ahern and Norton, 2020).
- Reproducibility, meaning that for a given building, by applying the same method, different assessors should receive the same EPC rating (Pérez-Lombard *et al.*, 2009; Arkesteijn and Dijk, 2010)

- Transparency in the sense that the EPC ratings are consistent (Stein and Meier, 2000; Pérez-Lombard *et al.*, 2009; Arkesteijn and Dijk, 2010).

While the EPC methodologies in different countries claim to have these characteristics intrinsic to them, numerous studies have demonstrated that the EPCs may be failing to stand up to the expectations, therefore, doubts about their real contributions to emission reductions have been rising.

Sesana and Salvalai (2018) believe that as the EPCs provide very general recommendation and they totally exclude indicators related to thermal and visual comfort and indoor air quality, they are rarely useful for the end-users. Tronchin and Fabbri (2012) stated that the effectiveness of EPCs should be evaluated based on two factors with the first one being the precision of the evaluation the assessor has carried out and the second one being the capacity of the energy classification bands to control the fluctuations in data input. According to Backhaus, Tigchelaar and de Best-Waldhober (2011) the quality of EPCs highly affects their aptness. Olaussen, Oust and Solstad (2017) took doubting EPC's usefulness to another level. In their study on Norwegian domestic sector, they questioned the EPCs existence as they believe given all the costs associated, the EPCs were not leaving an impact on people's choice of property. The authors suggest pondering over the idea of going for more direct regulations such as taxed.

One of the main reasons for questioning the real contribution of EPCs lies with the issue of their reliability. According to ZEBRA 2020 project (Toleikyte *et al.*, 2016), the reliability and credibility of EPCs has long been questioned by those involved in the real estate market. In more than 600 interviews with real estate agents in Austria, France, Germany, Italy, Norway, Poland, Romania and Spain, only 30% of the participants expressed a positive opinion about the reliability and usefulness of the EPCs while the negative comments were statistically significant (Toleikyte *et al.*, 2016).

EPCs reliability, or lack thereof, can be looked at from different aspects. One of these aspects is reproducibility (Ahern and Norton, 2020). As pointed out in preceding paragraphs this refers to a characteristic in which for a given building, applying a specific method results in the same EPC rating regardless of the assessor (Pérez-Lombard *et al.*, 2009; Arkesteijn and

Dijk, 2010), but there are studies suggesting that this is not always the case. For instance, Jenkins, Simpson and Peacock (2017) were triggered by concerns over consistency and quality of the UK domestic EPCs and conducted a study. They found that different assessors' evaluation of a single building using the same method, resulted in EPCs with considerable variations. In their study, 29 UK dwellings from different typologies were assessed and allocated an EPC rating by four different assessors using the same methods, models and procedures. The researchers found that almost two-thirds of the dwellings had EPC ratings varying by at least two bands. They also reported that for a few buildings, the differences were as significant as three bands. Contrary to this study, Tronchin and Fabbri (2012) asked 162 independent assessors to calculate EPC rating for the same building. The study found that despite the potential errors in methods, almost 72% of the assessors rated the building as band D. The study continued to claim that the structure of EPC generation in Italy supports some level of fluctuations from the input data, therefore the assessor's interpretation of input data would not affect the EPC rating.

It should be noted that in order to achieve an overall balance, trade-offs between accuracy, reproducibility, costs and the assessors' expertise are inevitable (Ahern and Norton, 2020). On the matter of receiving different EPC ratings for a given building, hence their reliability, the level of simplicity and complexity of the tool and amount of input data needed for running the simulation, can be impactful. According to Cayre *et al.* (2011), detailed and complex models cannot be used for the assessment of energy consumption of a large building stock due to the time constraints and lack of data, whereas, the simplified models - with fewer input data requirements compared to detailed models - can be used for a large building stock but usually an accurate assessment is not achieved and some rate of error would be inevitable (Cayre *et al.*, 2011). In a study in Edinburgh, different EPC bands were received for the same dwelling when a standard tool, i.e. SAP, and its version with reduced input data, i.e. RdSAP were used (Ingram, Banfill and Kennedy, 2011). It should also be noted that a more complex software tool may not always lead to a more reliable result. For instance, a study carried out on the quality of 2012 revision of French EPC showed that in spite of the considerable increase in the number of data required compared to an earlier version, inaccurate information and lack of robust input data could actually result in more uncertainty in the EPC rating (Osso *et al.*, 2019).

Another aspect affecting EPCs reliability, is estimations that considerably overestimate or underestimate the actual consumption. The EPCs of 8500 Greek dwellings were compared with their measured energy data by Balaras *et al.* (2016) and showed that on average, the EPCs were overestimating the energy consumption by 44%. Majcen, Itard and Visscher (2013) studied 200,000 domestic EPCs in Netherlands and found that the risk of overestimation of energy consumption is higher for the inefficient buildings. Also, the study showed that the buildings labelled as energy efficient, usually consume more energy than what is predicted for them by the EPC, reflecting underestimation of energy consumption. This has also been found by de Wilde (2014). The study looked at 20 non-domestic buildings in the UK, all of which except two, held EPC ratings of either band A (A+) or B. The buildings' EPCs were compared with their measured consumption, represented through display energy certificate (DEC) for public display. The study found that in 18 out of 20 cases, the EPCs were visibly underestimating the measured consumption. The two remaining cases - in which EPC ratings and measured consumption were consistent - were those with less favourable EPC ratings, band C and D (de Wilde, 2014).

The quality of EPCs hence their reliability also depends on the quality of input data. From energy policy point of view, it is required that the EPCs of buildings with the same use should be comparable. Using default and standard values, average and normative assumptions help to achieve this comparability, yet it may result in some inaccuracies especially for the research purposes (Laurent *et al.*, 2013). The same impact may be realised through normalising occupants behaviour (Laurent *et al.*, 2013). Also, the use of default values and standardised assumptions may result in an exaggeration of potential benefits from energy efficiency retrofitting measures. The main consequence of these unrealistic predictions is failing to achieve the expected reductions in energy consumption and CO_2 emission and having a longer payback period (Ahern and Norton, 2020).

Some researchers are of the idea that using theoretical and default values is an obstacle in the way of receiving the full benefits from energy efficiency policies, as the theoretical assumptions do not reflect the real conditions (Majcen, Itard and Visscher, 2013), adding more to the already controversial topic of EPC reliability. Hjortling *et al.* (2017) claimed that by generating the EPCs based on measured data from energy bills - as opposed to relying on theoretical calculations and default values - the Swedish EPCs are reliable.

Regardless of what caused it, issues with EPCs reliability affects their uptake as energy policy tools (Hårsman, Daghbashyan and Chaudhary, 2016). Furthermore, if the EPCs were not to be fully reliable, then the accompanying recommendations for improving the energy performance, cannot be trusted either (Jenkins, Simpson and Peacock, 2017).

The majority of the literature available for the EPC studies are focused on domestic buildings and housing stocks. That signals a gap in the literature concerning the non-domestic EPCs. The scarcity of information about non-domestic EPCs can be partly explained by the fact that until recent years, the amount of energy consumption hence CO_2 emission from the commercial building sector was much less than that of housing stock in the EU (Ürge-Vorsatz *et al.*, 2012). That may be one of the reasons that majority of energy policies are focused on the housing stock (Laurent *et al.*, 2013).

2.3 Building energy modelling and simulation

2.3.1 Role of building modelling and simulation

In recent years, due to an increase in the requirements of building codes, modelling and simulation has become an integral part of building design and retrofitting practices. The energy consumption of a building can be a function of a group of different factors such as building fabric specification, energy system specifications, control and maintenance, climatic situation, and occupant behaviour. The combined effects of these factors are not easy to predict, therefore the need for using building modelling and simulation is growing (Fumo, 2014). Building energy modelling was initially intended for evaluating the alternatives during the design stages (Al-Homoud, 2001; Gao, Koch and Wu, 2019), however, their applications have been extended to different stages of a building's life cycle (Augenbroe, 2002; Calama-González *et al.*, 2021). They are now an integral part of energy refurbishment proposals (Calama-González *et al.*, 2021) which is due to their significant role in narrowing down the options to the most energy efficient ones (Al-Homoud, 2001).

In the context of built environment, the energy modelling and simulation tools are usually thermal models. Using physical properties such as the U-values of the building elements, air permeability rate and efficiency of the HVAC systems, and exposure to outdoor weather conditions (Burman, Mumovic and Kimpian, 2014), "*a computer model of a building and its associated systems is created to determine parameters related to building performance*" (CIBSE, 2015, p. 5.7). Based on this definition they can be categorised in two main groups as below:

- **Steady state model:** The fundamental assumption in a steady state simulation tool is that all parameters involved are constant and their value does not change with time. As an example, in a steady state modelling and simulation tool, the "*U-value of building elements is used to predict one-dimensional heat transfer between two static environments and changes in heat storage are neglected*" (CIBSE, 2015, p. 5.6)
- **Dynamic model:** in a dynamic model, some of the parameters' values vary with time and calculations are carried out at specified intervals e.g., hourly intervals. Unlike the steady state model, here, time-related variations in thermal storage, weather, occupancy, etc. are allowed (CIBSE, 2015).

A more recent classification of building energy modelling and simulation divides them to engineering-based and data-based methods (Zhao and Magoulès, 2012, p. 3568; Fumo, 2014). Engineering-based methods rely on applying physics law and mathematical formulas. By nature, these models tend to be complex and uncertainties in the input data can yield inaccurate results (Babaei *et al.*, 2015). The data-based models, are gaining increasing popularity - due to growing knowledge in the field of machine learning - and they can handle some levels of uncertainty in input data (Krarti, 2003; Karatasou, Santamouris and Geros, 2006; Babaei *et al.*, 2015). While energy consumption data sets are used in both methods, they are an integral part to data-based methods (Babaei *et al.*, 2015).

2.3.2 Performance gap

Despite all the benefits of modelling and simulation tools, concern over the difference between estimated and the measured energy consumption is the subject of ongoing research in the field. Menezes *et al.* (2012) stated that despite all the significant progress and advancement in improving the quality of software packages for estimating the energy performance of the buildings, they are still struggling with issues in accurately predicting the energy consumption of a building especially with regards to occupant behaviour. Some levels of discrepancy between the two is inevitable due to uncertainties and intrinsic limitations of software tools (van Dronkelaar *et al.*, 2016) or as Oberkampf and Roy (2010) put it due to numerical errors in simulation and experimental variations in any observation (de Wilde, 2014), however, evidence from literature suggests that the levels tend to be beyond what can possibly be condoned (Norford *et al.*, 1994; Bordass, Cohen and Field, 2004; Pegg, Cripps and Kolokotroni, 2007; Menezes *et al.*, 2012; Petersen and Hviid, 2012; Tronchin and Fabbri, 2012; van Dronkelaar *et al.*, 2016; Hjortling *et al.*, 2017). This difference between the estimated and measured energy consumption is known as performance gap (Bordass *et al.*, 2001; Menezes *et al.*, 2012; Raslan and Davies, 2012; Burman, Mumovic and Kimpian, 2014; Cohen and Bordass, 2015; van Dronkelaar *et al.*, 2016; Rotimi *et al.*, 2017; de Wilde, 2018). A more specific definition is expressed by de Wilde (2014, p. 41): "*the energy performance gap is typically concerns predicted performance of the design intent with observed performance of the realized building over the year*". The issue of the gap between estimated and actual energy use has been reported in different countries (Zou *et al.*, 2018), however, the energy policy makers seem to prefer to ignore it (Gram-Hanssen *et al.*, 2017; Gram-Hanssen and Georg, 2018).

The performance gap can be attributed to a group of factors, from intrinsic limitations of simulation tools and methods (Lomas, 1996; Raslan and Davies, 2010; Calama-González *et al.*, 2021), to issues related to inaccuracy and/or uncertainties related to the input data (Ahmad and Culp, 2006; Menezes *et al.*, 2012). Also changes in the building commissioning (compared to the design phase assumptions) and issues related to building services management (Dasgupta, Prodromou and Mumovic, 2012) should not be dismissed. Overall, any assumption that deviates from the building's actual condition can result in discrepancy between the predicted and measured data (Hjortling et al., 2017). While the underlying causes of performance gap can occur at any stage of a building's life, i.e. design, construction and operation (Thompson *et al.*, 2021), many studies suggest that occupant behaviour has a huge impact on it (Menezes *et al.*, 2012; Balaras *et al.*, 2016; Brøgger and Wittchen, 2018; Happle, Fonseca and Schlueter, 2018).

With the risk of discrepancy between the simulation results and the measured data always present, model calibration can help in reducing the performance gap (de Wilde, 2014). Despite being necessary, calibrating simulation results can be challenging. Clarke, Strachan and Pernot (1993), mentioned in their work that one of the main challenges for calibrating a model is to decide *which* input data and to *what extent* needs to be changed for reducing the gap. According to the authors, the gap can also be attributed to a flaw in the simulation tool. Deciding on whether it is a misjudgement on determining an input data or a defect of the simulation tool requires high level of expertise (Clarke, Strachan and Pernot, 1993). The study on Birmingham airport by Parker, Cropper and Shao (2012) is a good example of how demanding calibration process can be. The authors updated 118 input data in order to calibrate their model of the airport. Raftery, Keane and Costa (2011) calibrated the whole building energy model of on office building in Ireland using hourly measured data through a version control software. With the number of datasets available for the study being significant, the authors stated that this level of accuracy in input data may not be available to many studies. Therefore, that high level of calibration may not be practical to many studies. In another study carried out by Bahadori-Jahromi *et al.* (2017) the researchers found that in order to calibrate their simulation of a hotel , they need to add the catering energy consumption according to the number of meals served in the hotel. By doing so, the researchers were able to reduce the gap between estimated and measured data considerably.

2.3.3 Simulation with purposes other than performance modelling

Although the necessity of validating the simulation results against the measured data is well emphasised in literature, it is important to know the purpose of simulation. In terms of the purposes behind a simulation, there are usually two formats: performance modelling and the compliance modelling. The former attempts to predict the future energy use of a building while the latter is carried out with the intention of checking for compliance with regulation (Thompson *et al.*, 2021).

Performance modelling is usually carried out at the design stage to predict the future energy consumption of a building (or to estimate the energy savings from a particular measure). As the building is not yet constructed, there are definitely uncertainties about some aspects related to the design, construction or operation (van Dronkelaar *et al.*, 2016). The modelling tool predicts the energy consumption of the building through the available input data and potentially some assumptions, signalling that this energy prediction is made with some incomplete information (Thompson *et al.*, 2021). Upon completion of the building, with the building services running and occupants using the building, it becomes possible to monitor and measure the actual energy consumption of the building. After the building has been in operation for some time, post-occupancy evaluation - the process of obtaining feedback on a building's performance in use (BRE, 2019b) - can help to assess the building's energy performance and decide whether it performs as planned. One of the widely recognised studies demonstrating performance gaps was carried out through a systematic post-occupancy evaluation called Post-occupancy Review of Buildings and their Engineering (PROBE), where 16 non-domestic buildings - all of which expected to be of high quality and exemplary design characteristic - were studied in detail. The study found that the energy consumption of most of these buildings were higher than the expectations. The study claimed that there were links missing between the design parameters, computer modelling assumptions and the actual values discovered in the buildings through the evaluation (Bordass *et al.*, 2001). According to Menezes *et al.* (2012), the performance gap in new builds is partially associated with the lack of feedback to the building designers after the handover. The post-occupancy evaluation can help the designers obtain feedback on the actual performance of the building when it is used and this information can be helpful in improving both the existing stock and future designs.

Similarly, the literature also suggests that the actual energy savings obtained after energy retrofit projects can be much less than the amount expected. This is usually due to the occupants opting for higher level of comfort in a new build or in a recently refurbished building (Burman, Mumovic and Kimpian, 2014). This behavioural response to the energy efficiency improvements are known as the rebound effect (Hirst, White and Goeltz, 1985). The rebound effect is more noticeable within the buildings with good energy efficiency ratings (Balaras *et al.*, 2016).

The International Performance Measurement and Verification Protocol (IPMVP) has set out a framework for calibrating the thermal models for energy retrofitting projects where whole-building simulation is required (Efficiency Valuation Organisation, 2012). According to the framework, calibration is achieved by adjusting the thermal model of the concerning building to reflect the as-built situation of the building accompanied by other actual considerations such as operating schedules. Upon calibrating the model with actual performance post-retrofit, systems and settings can be changed to pre-retrofit situations to provide the initial baseline. The energy saving obtained through the retrofit is the difference between "*energy performance derived from calibrated thermal model under pre-retrofit conditions, and the actual energy performance measured after the retrofit works*" (Burman, Mumovic and Kimpian, 2014, p. 156). Within this framework, in the absence of pre-retrofit energy performance, the whole-building calibrated simulation after one year of steady post-retrofit occupancy could be used (Efficiency Valuation Organisation, 2012; Burman, Mumovic and Kimpian, 2014).

As pointed out at the start of this section, the purpose of compliance modelling is to check whether the building meets the minimum requirements set out by building codes (Burman, Mumovic and Kimpian, 2014; Thompson *et al.*, 2021). Unlike the performance modelling, in compliance modelling the use of standardised operating conditions is necessary. Examples of which can be sought in the NCM, the UK's response to EPBD 2002, elaborated in section 2.2.2. As discussed previously, the application of standardised conditions is so that the intrinsic energy performance of the buildings with similar use is compared on a like-for-like basis (DCLG, 2015). Although using standardised conditions makes it easier for energy policy makers and regulators to compare the energy performance of buildings from similar category (Burman, Mumovic and Kimpian, 2014), it can also increase the performance gap (Williamson, 2012; Thompson *et al.*, 2021). There is evidence suggesting that the measured energy consumption can be up to five times higher than what was estimated by the compliance modelling (Carbon Trust, 2011; Menezes *et al.*, 2012). The compliance modelling can also overestimate the energy consumption of buildings, especially for those found to be from a poor energy efficiency rating (Balaras *et al.*, 2016) e.g. level E or below in EPC rating framework. This phenomenon is recognised as prebound effect and the risk of prebound effect increases as the level of inefficiency in the building's rating goes up. This is explained by the fact that the worse a building's energy efficiency level is, the more occupants try to minimise their energy consumption patterns (Sunikka-Blank and Galvin, 2012).

Irrespective of whether it overestimates or underestimates the building's operational energy consumption, some researchers are of the belief that the compliance modelling was never intended to be used for reflecting the actual energy consumption of a building (Morant, 2012; Burman, Mumovic and Kimpian, 2014; De Wilde, 2014; Thompson *et al.*, 2021). The reasons mentioned as to why the compliance modelling cannot be directly compared with the measured data are mentioned below.

- For the purpose of compliance modelling, standardised conditions - as required by EPBD 2002 - are applied to the models. The standardised conditions dictate many aspects, for instance, operational schedules for different zones within buildings, heating and cooling set points, hot water needs, etc. (More information on this is provided in chapter 3).
- Space heating and cooling, domestic hot water, lighting and auxiliary energy consumption are the five fixed end-uses considered in the compliance modelling and energy used for equipment, lifts and escalators, cooking equipment, etc. are not considered (Burman, Mumovic and Kimpian, 2014; Thompson *et al.*, 2021)

The visual presentation of the above is illustrated in Figure 2.2.

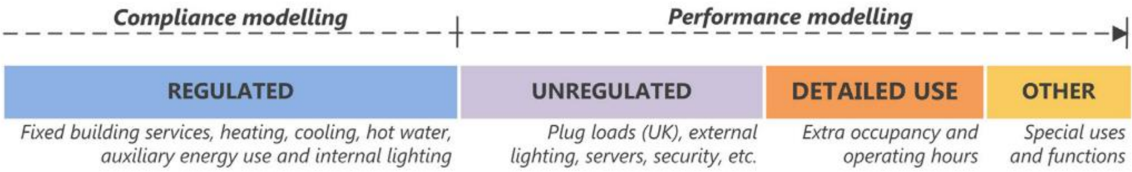


Figure 2.2 Representation of the excluded end-uses in compliance modelling (van Dronkelaar *et al.*, 2016)

2.4 Measures for improving the energy performance

In chapters 4 and 8, measures are applied for improving the EPC ratings of the hotels. In this section, existing literature concerning the impact of these measures on the energy performance of the buildings are discussed.

2.4.1 Glazing element

It is already well established that glazing can contribute heavily to buildings energy consumption (Ralegaonkar and Gupta, 2010; Jelle *et al.*, 2012; Mirrahimi *et al.*, 2016). According to the Commercial Buildings Energy Consumption Survey (CBECS), 34% of energy use in the commercial sector's space heating and/or cooling is caused because of the windows (Butzbaugh et al., 2018). Windows can be responsible for huge amount of energy loss in the buildings; numbers mentioned in the literature are as high as 30% (Aburas *et al.*, 2019) and even 60% (Jelle *et al.*, 2012; Cuce, 2018). This contribution to energy loss essentially comes with an increased level of CO_2 emission which is the focus of EPC assessments.

The energy performance of a window is assessed through thermal transmittance (U-value), total solar energy transmittance (g-value), and air leakage (Urbikain and Sala, 2009; Cuce and Riffat, 2015; Djamel and Noureddine, 2017). Compared to other building elements, windows have a remarkably higher U-value (Cuce and Riffat, 2015). Where the U-value – the rate of heat transfer through a structure (whether a single material or a composite of several layers), divided by the difference in temperature across that structure (Lymath, 2015) - of a new building's roof, floor, and external wall are expected to be in the range of 0.25 to 0.35 W/m^2K, it can reach up to 2.2 $W/m^2.K$ for a window (HM Government, 2010). However, due to their role in daylighting and ventilation and their psychological impact on occupants (Jaber and Ajib, 2011), windows cannot be avoided in a building. Therefore, careful choice of glazing type (Hassouneh, Alshboul and Al-Salaymeh, 2010) and optimised window dimensions (Foroughi, Asadi and Khazaeli, 2021) are necessary for reducing the energy loss through the windows.

Usually, the heat loss in windows occur through the following mechanisms:

- Air leakage around the opening sashes
- Air leakage around the window frame

- Conduction through the glazing spacer bars
- Conduction through the window frames
- Radiation through the glazing (Cuce, 2018)

Another point to be considered is that although convection is usually not considered as an influential means of heat transfer in windows, the depth of the gap between the glazing layers can increase the heat transfer through conduction to a considerable amount. In window units with increased gap between the glazing layers, the air becomes warmer in the vicinity of the warmer pane – the inner pane during the colder times of the year. Due to buoyancy effect, the warm air rises and is replaced by the cooler air, resulting in a convection current causing a heat loss from the warmer pane to the colder one (Cuce, 2018). In recent decades, efforts have been made to improve the thermal performance of glazing systems through advanced technologies; from multi-layered glazing, to vacuum glazing, window films, aerogels and switchable smart windows (Jelle *et al.*, 2012). The arrangement of liquid crystals within them can change by applying electricity, heat and/or light. This results in alterations of light transmission properties, enabling the glass to switch from transparent to translucent and vice versa.

2.4.2 Window films

One of the measures for improving the thermal performance of windows without causing much disturbance to the occupants is applying window films (Li *et al.*, 2015). The application of window films can be for purely aesthetic purposes, a need for privacy or to improve the energy performance of the building. Within the latter category, there are different types of window films targeting different aspects of windows. For example, sun control window films tend to reduce cooling energy consumption through a decrease in solar gain (Bahadori-Jahromi *et al.*, 2017). They can also reduce light transmittance (Moretti and Belloni, 2015). This quality is most suitable for a hot climate (Mohelníková, 2011). Apart from reducing the cooling load, sun control coatings may also increase the heating loads due to reductions in solar gains (Yin, Xu and Shen, 2012; Bahadori-Jahromi *et al.*, 2017). The final impact on the annual energy consumption is a function of the balance between heating and cooling energy consumptions.

Low-*E* (Low-emissivity) film is another type of window film widely in use. Emissivity is a measure of an object's ability to emit infrared energy. Low-*E* films are based on metals or metallic oxides, offered in two different types: soft and hard. Compared to the hard coatings, the soft low-*E* films are less durable (Cuce and Riffat, 2015). Low-*E* films are useful in reducing both the heat gains and also heat loss through the windows. Low-*E* films are known to be spectrally selective, and this characteristic makes them strong reflectors in the infrared region. Due to this ability, the low-*E* films reflect the longwave infrared radiation from an indoor space back inside, or in other words, result in the heat being trapped inside and that's how the heat loss is reduced significantly (Rezaei, Shannigrahi and Ramakrishna, 2017). This aspect of the Low-*E* coatings is essentially effective for heating dominant areas.

By reducing the solar transmittance, Low-*E* coatings cause a reduction in heat gain, which is obviously of high importance for cooling dominant areas. However, a real saving in cooling energy consumption is only achieved if/when the reduction in heat gain exceeds the heat loss reductions caused by the film's low emissivity. Otherwise, their inherent ability to trap heat inside will not be helpful in reducing the cooling energy consumptions in hot climates. This means some glazing solutions' maximum performance is only achievable in one specific climatic situation (Costanzo, Evola and Marletta, 2016). Similar to this finding, Ye and colleagues (2013) claimed that a Low-*E* coating suitable for summertime might not necessarily suit the needs of winter time, as its capability in reducing the emissivity is usually followed by a reduction in light transmittance. The study by Wang and Shi (2017) found that that Low-*E* coatings with high solar heat gain coefficient (SHGC) will perform better in heating-dominant climates, while the ones with low SHGC will be more suitable for cooling dominant conditions.

Although the application of Low-*E* coatings has become more common in recent years, their benefits have been known for more than three decades. In the study by Sweitzer, Arasteh and Selkowitz (1987) - one of the first studies on these coatings - it was found that Low-*E* coatings are beneficial in reducing both heating and cooling and even lighting energy consumption. The findings of the study were based on buildings with various window-to-wall ratios in both cold and hot climatic situations. In another study by Collins and Simko (1998), heat transfer mechanisms in vacuum glazing units were modelled and compared with the experimental data. The study found that when Low-*E* coatings were added, the units' heat loss through radiation was reduced considerably. Fang and colleagues (2013) also focused on vacuum glazing units and studies its thermal performance. They constructed a guarded hot box calorimeter to validate the result of the simulation they carried out. By adding an extra layer of Low-*E* coating (three in total), the glazing unit hit a significantly low U-value of 0.24 W/m^2K, although in reality, applying three layers of Low-*E* coatings might not be financially viable.

Karlsson and Roos (2001) mentioned that when applied properly, Low-*E* coatings can achieve high levels of energy savings. They also stated that since its introduction in early 1980s, the Low-*E* thin film technology had achieved its maturity by the time of the research - 2001 - and had secured its position as a cost-effective measure for energy savings in most cases. Other researchers may not agree with this study about the cost effectiveness. For example, Chow, Li and Lin (2010) and Gorgolis and Karamanis (2016) stated that Low-*E* films' high production cost acts as an obstacle in a wider application of them.

As briefly illustrated in the paragraphs above, there is a relatively large body of knowledge about the impact of Low-*E* window films on energy consumption of buildings in different climatic situations, however, none of these studies are in the context of EPC rating.

2.4.3 Combined heat and power (CHP) systems

Energy efficiency is among the main contributors to climate change mitigation. Over the years, it has become clear that the conventional approach, in which a building's energy demand is met through grid-supplied electricity and/or through burning fuel in a boiler is not very efficient. Depending on the type of fuel used, the generation and supply of electricity in power stations take place with an efficiency in the range of 25%–50%, considering the losses sustained through transmission (CHPQA, 2021). This efficiency of 25%–50% means that 50%–75% of energy content of the fuel has not been used. In other words, a considerable amount of energy has been wasted as heat, rejected directly into the atmosphere (CHPQA, 2021). This high level of inefficiency in the conventional means of energy production is one of the main reasons that distributed energy resources (DER) are gaining more popularity. Those involved in the field have high hopes that using DER can help in tackling today world's environmental issues (Alarcon-Rodriguez, Ault and Galloway, 2010). DERs refer to sources for small scale generation of electricity, which is located in close proximity to the user (Capehart, 2016), therefore, compared to the grid-supplied electricity transferred from large-scale plants through high-voltage transmission lines, reduced amount of power loss can be achieved.

Different systems, ranging from renewable energy sources such as wind power, geothermal power and photovoltaic to cogeneration and trigeneration systems are all recognised as DER systems (Alarcon-Rodriguez, Ault and Galloway, 2010; Capehart, 2016). Cogeneration or combined production of heat and power (also known as CHP) refers to the technology by which heat and power are jointly generated by one unit, using waste heat as a co-product of the electricity generation (DFIC, 2016). Using this by-product heat that would otherwise be wasted is the reason for high efficiency of this system. Compared to the conventional means in which heat and power are generated separately for example through a boiler and power station, the CHP technology can provide an overall efficiency of 80% and up to 30% reduction in CO_2 emission (BEIS, 2013).

Regardless of the type of technology applied, a CHP plant is comprised of an electrical generator combined with apparatuses for recovering and using the heat from the generator. This heat is then used for space heating or hot water, or further used space cooling in combined cooling, heating and power production systems known as trigeneration or CCHP systems (Mago and Smith, 2012).

In the UK, benefits of CHP technology have been known for quite a while now. In 2004, the European Parliament introduced the Directive 2004/8/EC on the promotion of cogeneration based on a useful heat demand in the internal energy market (Directive 2004/8/EC, 2004). Since then, the UK Government has supported the development of cogeneration and even introduced initiatives such as CHP Focus to offer financial helps to users (BEIS, 2013). Furthermore, schemes are in place for ensuring the quality of the CHP systems, such as CHP Quality Assurance Program (CHPQA) aiming to monitor, assess and improve the quality of this technology in the UK (BEIS, 2014; CHPQA, 2021).

Although CHP can use a variety of fuels (e.g., petroleum products, coal, renewables), for the time being, natural gas remains the main fuel consumed in CHP plants. According to the Digest of UK Energy Statistics (DUKES) annual data for 2020, natural gas held a share of 72% among all the fuel input for CHP systems in the UK, while the share of renewable fuel (including bioliquids, solid biomass, biogas and waste) was reported around 15% (Waters, 2021). According to the same report, emission savings from CHP systems - compared to conventional generation of heat and electricity - amounted to 9.66 $MtCO_2$ in 2020, compared to all fossil fuels (Waters, 2021).

When implementing a CHP system, it should be remembered there are factors that affect the overall performance and efficiency of the system including CHP system's sizing, different components' efficiency and the building loads (Dorer and Weber, 2009; Hueffed and Mago, 2010; Mago and Smith, 2012). Among these, correct sizing of the CHP system is of high importance. When sizing a CHP system, two approaches can be followed: one is to size the system based on the electric load and employ the by-product heat for satisfying the building's thermal need. The other approach is to size the CHP system based on the thermal load and use the generated electricity to meet the electricity needs of the building (Mago and Luck, 2013). These two approaches have been the subject of many studies (Cardona, Piacentino and Cardona, 2006; Mago, Chamra and Hueffed, 2009; Mago, Fumo and Chamra, 2009; Hueffed and Mago, 2010). Choosing the right approach depends on the power generating unit loading and some other factors such as how to deal with excess electricity - i.e. to sell it to the grid or possibility of storing it on-site (Cardona, Piacentino and Cardona, 2006). On the other hand, sizing the CHP to deliver a thermal load equivalent to the building's base heat load (Wang *et al.*, 2015; Magnani, Pezzola and Danti, 2016) can ensure that the heat produced during the electricity generation is used efficiently – as there is always demand for it. Depending on whether this results in generating more or less electricity than needed, it can be dealt with through selling to or buying from the national grid accordingly (Salem *et al.*, 2018). Regardless of the approach taken, it should be remembered that the electric and thermal demand in the building vary constantly due to different factors such as level of occupancy and weather situation, therefore, the power generating unit does not always operate at full load (Mago and

Luck, 2013). According to Wang and colleagues (2015), a CHP system can achieve its highest potential efficiency when operating at full power under the optimal assigned heat to power ratio.

2.5 Summary of the chapter

The following points are the main findings from the studies reviewed in this chapter:

- Hotels are among the most energy intensive buildings.
- Depending on the type, level of facilities and climatic conditions, energy benchmarks for hotels can vary a lot.
- Choice of measures for improving the energy performance of a hotel can be highly affected by the climatic conditions.
- Despite the differences in methodologies, most countries rely on whole building thermal simulation for calculating the EPCs.
- Using standardised conditions is important for comparability of buildings with the same use.
- Apart from communicating the energy performance of buildings, other roles such as signalling market values and policy tools were expected from EPCs.
- Concerns about EPCs' effectiveness and their reliability have arisen in different countries.
- Some level of gap between estimated data (through simulation tools) and measured data is inevitable. In performance modelling, calibration of the model is triggered by comparing the simulation results with the measured data.
- Compliance modelling is conducted to check for adherence with minimum requirements. Compliance modelling is not reflective of the actual situations in a building, and it cannot be compared with the measured data.

Chapter 3 Methodology

In this chapter, the steps taken for carrying out this research are explained in full details. By discussing the research paradigm and design and the specific method of data collection, the research approach is explained in full. Then, the current approved procedure for calculating non-domestic EPCs for England and Wales is explained. The chapter then continues to explain how this procedure is carried out in TAS; the main tool used in this study.

3.1 Research approach

After choosing a topic to study and investigate, the next step for the researcher is to consider how she/he wants to carry out the study. Research methodology provides the research process: how it will proceed. The process depends on the way the researcher thinks about the problem and how it should be studied so that the study itself and its findings can be deemed credible in the related discipline (Chilisa and Kawulich, 2012). Regardless of the type of terminology used for describing this process, there are some main components involved. The three main components are research paradigm (philosophy), research design and specific research method (Creswell, 2014). Usually choosing a methodology begins by a paradigm the researcher picks in order to conduct the study. Upon making this decision, the methodological process is planned. Several important factors will have an impact on the methodological process such as the philosophical beliefs and theoretical frameworks. While the former is more concerned with the nature of reality, knowledge and values, the latter informs comprehension, interpretation and the choice of literature on the given topic (Chilisa and Kawulich, 2012).

3.1.1 Research paradigm

The researchers' thoughts and ideas on what constitutes the truth and knowledge, guide their thinking, beliefs and assumptions and frame their understanding of the world and is called research paradigm (Chilisa and Kawulich, 2012). It can also be described as a guiding principle for the research in terms of "*general philosophical orientations towards the world and the nature of the research that the researcher brings to the study*" (Creswell and Creswell, 2018, p. 5). It has been stated that certain paradigms associate with specific research methodologies (Chilisa and Kawulich,2012) although the choice of the research paradigms depends on the research question, researcher's background and discipline orientation and previous expertise in the field (Creswell and Creswell, 2018).

Regarding the nature of this research, which is a scientific research in the field of engineering, the post positivism research paradigm will be followed. In order to discuss what is involved in this paradigm, it seems necessary to begin by a brief discussion on positivism paradigm. Positivism believes that truth and objective reality is only achievable through scientific method, and science can be the only foundation to establish true knowledge (Chilisa and Kawulich, 2012). In this philosophy's view, one cannot make any claims about knowledge, unless it is directly based on experience (Bogdan and Biklen, 2003). Post positivism philosophy has many aspects in common with positivism, however, its view towards science is less strict (Chilisa and Kawulich, 2012). This paradigm is of the belief that even when the researcher tries to fully comply with a scientific method, it is still possible for the research outcomes to be "neither totally objective, nor unquestionably certain" (Crotty, 1998, p. 40). In essence, post positivism is a version of positivism philosophy where there is no claim of a privileged position for the scientific method (Crotty, 1998). Both of these paradigms believe that there is a reality independent of the researcher's thinking, which can be investigated through scientific methods. Despite this shared belief, post positivism believe that this reality can only be perceived imperfectly and within a certain realm of probability due to intrinsic human limitations (Chilisa and Kawulich, 2012). Upon choosing the post positivism, the researcher accepts that the nature of knowledge is objective, what counts as knowledge is based on observation and measurement, the methodology is quantitative and gathering the data heavily relies on techniques such as observations, questionnaires and test and experiments (Chilisa, 2011).

3.1.2 Research design and research model

Research design is the type of inquiry within the research approach that defines the specific direction each and every step in the research process needs to take in order to find the answers for the research questions (Creswell and Creswell, 2018).

The research questions of this study can all be addressed using a quantitative methodology. The data collected and analysed will all be numerical data. Within this context, the research design for this study can be laid out as described below.

As the focus of this study is on hotel buildings, with regards to the background research done earlier which helped in coming up with the research questions, the first step would be to carry out a more detailed investigation and exploration of the existing knowledge concerning different aspects of energy consumption in hotel buildings. Obviously, this was done by the literature review which is an ongoing task throughout the study. The literature review, however, was not limited to only one scope. Energy certification schemes in non-domestic buildings and related issues were also investigated and searched for, the results of which were provided in detail in chapter 2.

Quantitative research in engineering studies relies to a great extent on modelling and simulations, and monitoring and measuring equipment (Borrego, Douglas and Amelink, 2009). Current methods in building modelling and simulations include "*engineering, statistical methods and artificial intelligence methods*" (Brøgger and Wittchen, 2018). Building modelling and energy simulation software are among the engineering tools. The specific method used in this research (or the technique to collect data), is Thermal Analysis Software (TAS), a product of Engineering Development Solutions Limited (EDSL). TAS is fully accredited for the UK Buildings Regulations 2013 compliance assessment. It is also accredited by the Chartered Institution for Building Services Engineers (CIBSE). Further information on TAS modelling and simulation process is provided in section 3.3.

When using building modelling and simulation, the common practice is to validate the model to ensure its reliability. That is to compare the simulation results with the measured data and if the gap is within an acceptable range, then the model is deemed reliable. However, as discussed in chapter 2, due to the concepts behind a compliance modelling (following standardised condition, accounting for only fixed building services, excluding the energy use by equipment, lifts, and cooking equipment) the measured data cannot be used for validating the result of a compliance modelling, see section 2.3. Therefore, in this study, the results of the simulations are compared with the measured data only as a means of deciding whether the simulation overestimates or underestimates the actual energy consumption and not a means of validation.

After these steps, the data analysis starts. Depending on the specific aims and objectives for each simulation, statistical analyses are carried out on simulation results, for example, Sensitivity Analysis. Here, Differential Sensitivity Analysis (DSA) - detailed in chapter 7 - is carried out to identify the key parameters in determining a hotel's EPC rating.

3.2 Methodology for calculating the EPC rating of a non-domestic building

3.2.1 Definition of Reference building

As mentioned in chapter 2 section 2.2.2.3, for the purpose of calculating the asset rating hence issuing the EPC, apart from the actual building's estimated CO_2 emission rate, the emission rate from a "reference building" is also needed. The Reference building has the same size, shape and zoning arrangements as the Actual building. Whatever specification is assigned to the Actual building in terms of building orientations, type of activity in the zones, exposure to outdoor weather and the type of building services, will also be applied to the Reference building, however, for the purpose of consistency in comparisons, there are certain assumptions about the Reference building that should be followed, irrespective of the situation in the Actual building, for instance U-values of the building fabric element, type of fuel used for heating and hot water, etc. Table 3.1 shows these assumptions. The default assumptions for Reference building e.g. the U-values of the building fabric, are set by the NCM modelling guide (DCLG, 2013). The guide was last updated in November 2017. It should be mentioned that Table 3.1 does not provide the full list of assumptions for Reference building. Information on all the assumptions regarding the Reference building can be found in National Calculation Methodology (NCM) modelling guide (for buildings other than dwelling in England and Wales) (DCLG, 2013).

Table 3.1 Comparing the assumptions for the Actual and Reference buildings (DCLG, 2013)

		Actual building	Reference building
Physical aspects	**Size, shape, orientation**	According to the real situation	Same as Actual building
	Outdoor weather	According to the real situation	Same as Actual building
	Thermal zones	According to the real situation	Same as Actual building
	Indoor activities	According to the real situation	Same as Actual building
Building fabrics	**U-values of building elements**	According to the real situation	Default values set by NCM.
	Glass properties, solar and light transmittance	According to the real situation	Default values set by NCM.
HVAC systems	**Space heating and hot water service**	According to the real situation	Always met by natural gas
	Heating set point	If the space in the Actual building has a heating system, then it will be heated up to the heating set-point as defined in the NCM Activity database.	Same as Actual building
	Cooling set point	If the space in the Actual building has a cooling system, then it will be cooled down to the cooling set-point as defined in the NCM Activity database.	Each conditioned zone will be cooled with a fixed cooling set-point of 27^{o}C, irrespective of whether the zone has cooling provisions in the Actual building or not.
Infiltration	**Air permeability rates**	As defined in CIBSE Guide A infiltration tables	10 $m^3/(h.m^2)$ @50 Pa

3.2.2 Calculating asset rating

The CO_2 emission rate arising from the use of fixed building services in the Reference building is calculated, which is referred to as Reference building Emission Rate (RER). This value is then "*adjusted by the relevant improvement factor, to arrive at the energy performance used to normalise the CO_2 emissions in the Actual building*" (DCLG, 2013, p. 46). The resultant of multiplying the RER by the improvement factor is termed Standard Emission Rate (SER), Equation 3.1. The asset rating (AR) is the ratio of the Actual building Emission Rate (BER) to SER, with the result normalised such that the SER is equivalent to an AR of 50 (DCLG, 2013), Equation 3.2. The result of the Equation 3.2 determines the EPC rating of the building, Table 3.2.

$$SER = RER \times 0.765 \tag{3.1}$$

$$AR = (BER \div SER) \times 50 \tag{3.2}$$

Table 3.2 EPC ratings scale and energy bands

Scale	EPC Band
0.00 ≤ **AR** ≤ 25.0	A
25.0 < **AR** ≤ 50.0	B
50.0 <**AR** ≤ 75.0	C
75.0 <**AR** ≤ 100.0	D
100.0 <**AR** ≤ 125.0	E
125.0 <**AR** ≤ 150.0	F
150.0 <**AR**	G

3.2.3 Input data from NCM Activity database

In chapter 2, section 2.2.2, it was explained that NCM is the UK's response to the requirements set by the EPBD 2002 and was developed to carry out the calculations for buildings energy performance compliance and asset rating. Through NCM, estimating buildings energy performance on a consistent basis is facilitated (DCLG, 2013). A key part of the NCM is an Activity database that contains a comprehensive list of buildings - for instance, retails, restaurants, hotels, offices, hospitals. The NCM then divides each building into a series of activity zones, that may have different internal conditions or operation schedules. This would be specifically helpful when there is a mixture of different uses in a particular building, such as what happens in a hotel building. Full list of these buildings and the activity types within the buildings can be found in (DCLG, 2015).

For the purpose of achieving consistency in comparing buildings with similar use - which may have different actual operating schedules and patterns - the NCM Activity database determines some of the parameters. This means that these parameters in each activity zone are fixed rather being left to users' choice. These parameters are:

- Heating and cooling set points
- Ventilation standards
- Lighting standards
- Occupant density and the related internal gains
- Gains from equipment
- Internal moisture gains in the case of swimming pools and kitchens
- Working/operating schedules during which the above parameters are maintained and set back conditions for when they are not maintained
- Hot water demand (DCLG, 2013, 2015).

3.2.4 Approved tools

According to the Notice of Approval (MHCLG, 2018), the approved methodologies for expressing the energy performance of buildings are:

I. The Standard Assessment Procedure (SAP) for the energy rating of dwellings
II. The Government's Simplified Building Energy Model (SBEM) latest version
III. Approved Dynamic Simulation Models:
   - Environmental Design Solution Limited TAS (EDSL TAS) version 9.4
   - Integrated Environmental Solutions Limited Virtual Environment (IES VE) version 7.0
   - Bentley Systems (UK) Ltd Design Simulator version 26.06 (MHCLG, 2018)

3.3 Introducing TAS

3.3.1 TAS, dynamic simulation software

As mentioned previously, building modelling and simulation software, TAS is used throughout this study to model and simulate the energy performance and EPC rating of hotels. While there are other commercially available simulation tools that can be used for estimating energy performance, only three dynamic simulation tools are accredited by the UK Government for the purpose of generating EPCs (listed in section 3.2.4), among which TAS is the first one. The choice of TAS over the other two software tools was based on its capabilities, ease of use and the type and range of outputs it provides. TAS is capable of modelling large complex buildings. It's engineering version comes with a modular design, which means it has dedicated programs each serving a specific purpose and leading a methodical workflow. These modules are 3D Modeller, Building Simulator, Result Viewer, Systems and Utilities.

TAS adopts a dynamic approach for thermal simulation, meaning that the thermal state of a building is traced through a series of <u>hourly</u> snapshots during which, the influence of different thermal processes occurring in the building, their timing, location and interaction is calculated. Heat balance method is applied for carrying out the dynamic simulation and it is known to be the most scientifically rigorous method for this purpose. Within the assumptions and approximations needed for thermal modelling of this type (i.e., uniform temperature for air within one zone due to its motion, uniform surface temperatures for different building elements in the zone, etc.), the heat balance method incorporates the following four distinct processes:

- The **external face** heat balance which consists of absorbed (direct and diffuse) solar radiation, convective heat exchange with the outside air and long-wave radiation from the surroundings.
- The **wall conduction** process which happens due to difference in the temperature of the walls internal and external surfaces.
- The **indoor face** heat balance which consists of short-wave radiation from lights, long-wave radiation from equipment and internal sources, long-wave radiant

exchange between different surfaces, transmitted solar radiation flux absorbed at surfaces and convective heat flux to zone air

- The **air** heat balance which consists of heat transfers from the HVAC system, sensible load due to infiltration and ventilation and convection heat transfer from the surfaces (Pederson, Fisher and Liesen, 1997).

3.3.2 Heat transfer mechanisms in TAS

As mentioned in the previous section, TAS adopts a dynamic approach, which allows the influence of thermal procedures occurring in the building, their timing, location and interaction, to be properly accounted for. Figure 3.1 shows a schematic illustration of these processes, showing the movement of heat in various forms as it is transferred into, out of and around the building by a variety of mechanism, including conduction, convection, long-wave radiation, and solar radiation.

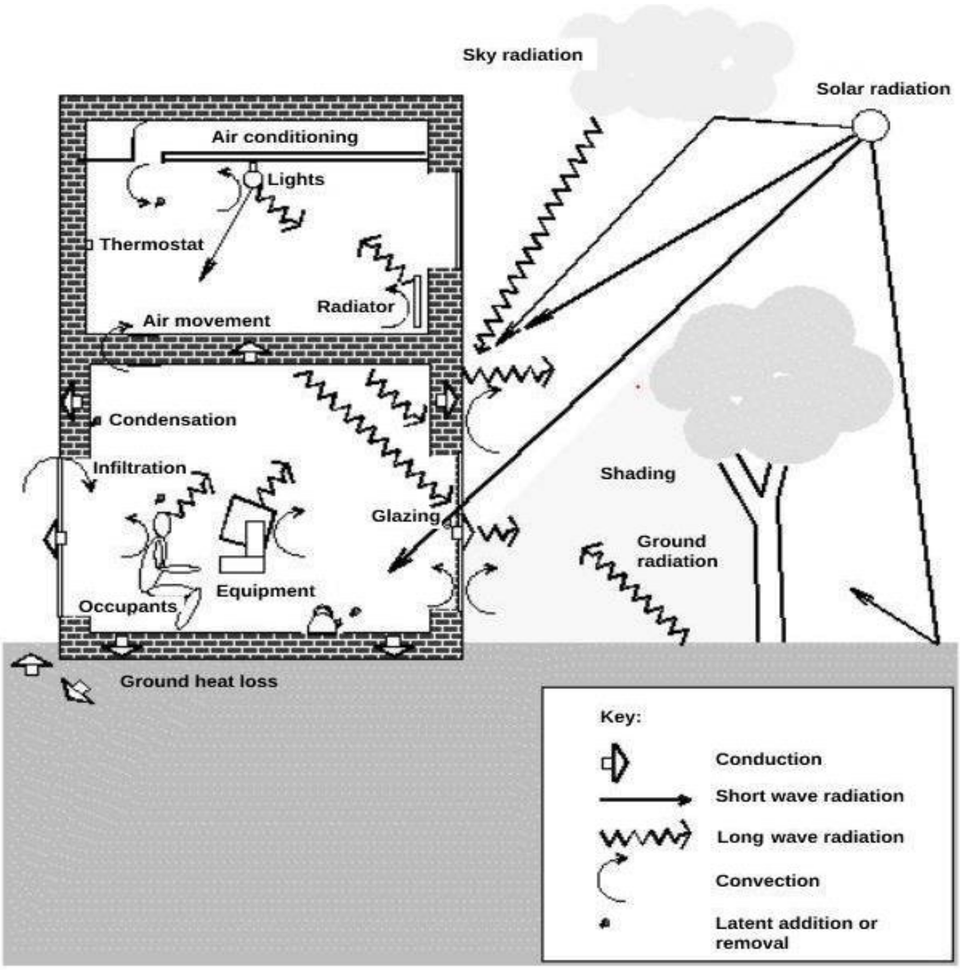


Figure 3.1 Schematic illustration of heat transfer mechanisms considered in TAS (EDSL TAS, 2018)

The heat transfer mechanisms considered in TAS are listed below:

- Conduction in the fabric of the building,
- Convection at building surfaces and external convection due to wind speed (if applicable)
- Long-wave radiation exchange between surfaces and also long-wave radiation from the sky and the ground
- Solar radiation absorbed, reflected, and transmitted by each building element.
- Gains (from occupant, equipment, lighting, etc.) by resolving them into radiant and convection portions.

Natural ventilation is also considered through air flows arising from wind and stack pressures. Infiltration, ventilation, and air movement between different zones of the buildings can cause heat transfer, therefore they are considered in the overall calculations too. The sensible heat balance for each zone is then calculated through equations representing the individual energy balances for the air and each of the surfaces, combined with equations representing the energy balances at the external surfaces of the building. The whole equation set is then solved to calculate the air and surface temperatures and loads (heating, cooling, and sensible loads). This procedure is then repeated for each hour of the simulation (EDSL TAS, 2018).

3.3.3 Modelling process

3.3.3.1 What input data is needed?

Like other energy modelling software of this kind, TAS needs certain inputs for modelling the thermal behaviour of the building. Some of the parameters that affect the building's thermal performance are listed below:

- Thermal insulation
- Glazing properties
- Built form and orientation
- Climate
- Shading from adjacent buildings and self-shading
- Infiltration

- Natural and/or mechanical ventilation
- Solar gain
- Gains from lights, occupants, and equipment (both sensible and latent)
- Control set points
- Plant schedules
- Performance of boilers, heat pumps, etc.

The information needed for these parameters are acquired through different means, from site visits and collecting the architectural drawings, from standard weather files to applying the appropriate activity type from NCM Activity database to zones. The process is described in the following section.

3.3.3.2 Modelling process

As mentioned, some of the information is collected during site visits, where the building's architectural drawings e.g., plans and sections are collected and compared with the existing situation to check for any alterations in the building. This is an important step as there might have been changes in the building since those drawings were produced. For instance, a zone/space may now be used for a different purpose compared to what was assigned to it originally. Depending on when the drawings were produced, they may not reflect all the changes and current situations in the building. Apart from measurements of the spaces within the building (length, width and height) and measurements of windows/doors, the following information is also collected:

- Information about the building's construction, such as construction material and the year of construction. The former is needed for fabric specification such as building elements' thermal transmittance (U-value) while the latter can be helpful in estimating the air permeability rate and looking up the typical construction material of the time in case precise data is not available. Measurements of windows, doors and floor heights are noted.
- The usage of different rooms and spaces needed for specifying thermal zones in the software.

- Fixed, built-in services and the specification of their concerning systems, such as systems efficiency and their type of fuel. The fixed, built-in services are those related to heating, cooling, ventilation, hot water, and lighting, based on the EPBD requirements (See chapter 2, section 2.2.).

When all the data from the site is collected, existing drawings - usually in AutoCAD format - are updated, if necessary. The updated AutoCAD drawings are then used to create a refined floor plan containing all the existing zones such as guest rooms, offices, restaurant/café, laundry, gym, etc. This step is important as the type of zones (further used to pick the appropriate activity from NCM Activity database) and their sizes have a direct impact on the estimated energy consumption and CO_2 emission rate. When the refined floor plans are ready, the modelling starts in TAS 3D Modeller by importing the plans with a reference line. Upon importing the CAD files, the scales are also checked and corrected if needed. The building's exact location can be entered using the latitude and longitude. When all the physical aspects of the buildings such as walls, floors, ceilings and roof, doors and windows are modelled, the zones are specified and given a name for future reference. After ensuring there is no error in the 3D model, using an analysis tool of the Module, the building is generated, and zones' area are calculated.

The 3D model is then taken into the Building Simulator Module, where all the thermal interactions and heat transfer mechanisms are calculated, as discussed in section 3.3.2. At the start of this step, building summary including the number of zones and building elements and total zone floor area can be checked.

This module requires further input information e.g., weather data, calendar, zones' internal conditions, building elements' construction, etc.

Weather data is used as the climatic input for TAS simulations. Test Reference Year (TRY) and Design Summer Year (DSY) are available for different stations around the UK. They are developed by CIBSE based on hourly values of variables such as air temperature, wind speed and direction etc. measured by the UK Meteorological Office. The TRY is used for energy analysis and compliance with UK Building Regulations and is composed of 12 separate months of data each chosen in a way that it represents the most average month from the data collected (from 1984 to 2013). The DSY is used for overheating analysis and it is a continuous year rather than a composite one from average months (CIBSE, 2017b). For the purpose of EPC calculation, TRY weather files should be used.

Information about the internal conditions of each zone is needed in this Module, including occupancy rates, density of people, heating and cooling set points, lighting levels, DHW need, etc. In a building as complex and sizable as a hotel, this information can be either changing frequently e.g., the occupancy rate and density of people or very difficult to collect e.g., the DHW demand. However, as explained previously, for EPC assessment, the standard profiles from NCM Activity database should be used. This is to achieve consistency in comparing buildings with similar use, see section 3.2.3. A comprehensive list of assumptions for different types of activities within a hotel is provided in Table 3.3.

Table 3.3 NCM standard profiles assumptions for different activities within a hotel

Zone	**Occupancy hours**	**People density (pers/m²)**	**Metabolic rate (W/p)**	**DHW need (l/m² per day)**	**Room illuminance (lux)**	**Heating and cooling set points (°C)**
Changing area	9:00 to 22:00	0.119	140	120.0	100	H: 22 C: 25
Circulation	7:00 to 23:59	0.114	140	0	100	H: 20 C: 23
Eat/drink area	Variable from 7:00 to 23:59	0.187	110	8.0	150	H: 23 C: 25
Dry sport hall	9:00 to 22:00	0.041	300	0	300	H: 16 C: 25
Ensuite bedroom	00:00 to 10:00 21:00 to 23:59	0.094	104	13.12	100	H: 21 C: 25 (At all times)
Fitness/gym	9:00 to 22:00	0.140	300	0	150	H: 18 C: 25
Food prep/kitchen	Variable from 6:00 to 23:59	0.108	180	0.33	500	H: 17 C: 21
Hall	9:00 to 22:00	0.183	140	0.6	300	H: 20 C: 23

Laundry	8:00 to 19:00	0.121	180	0	300	H: 18 C: 27
Office	7:00 to 20:00	0.106	123	0.221	400	H: 22 C: 24
Plant	9:00 to 18:00	0.11	180	0	200	Not considered
Reception	7:00 to 23:59	0.104	140	0.03	200	H: 20 C: 23
Store	7:00 to 22:00	0.11	140	0	50	H: 20 C: 23
Swimming pool	9:00 to 22:00	0.139	160	0	300	H: 26 C: 32
Toilet	7:00 to 22:00	0.117	140	0	200	H: 20 C: 25

Apart from the mandatory assumptions from NCM Activity database, every measure is taken to ensure that the model is a close representative of the actual building in other aspects, i.e., building size and orientation, windows and glazing elements, zones, and their geometries, assigning the right activity type to each zone, etc. At the end of this stage, again the model is checked for errors. Then first round of simulation is carried to calculate the building loads. The product of the Building Simulator Module is a TBD file standing for TAS Building Data.

The TBD file is taken into TAS Utility: Building Regulation Studios where the existing fixed services, i.e., heating, cooling, DHW and lighting are all replicated. The type of ventilation (natural/mechanical) is also assigned in this module. When all the information is submitted to the studio, the final round of simulation can start. The output of this round of simulation is a document checking compliance with the main criteria in Building Regulation Part L (see chapter 2, section 2.2.2.2) followed by an EPC rating. Figure 3.2 shows the modelling and simulation process in a flow chart.

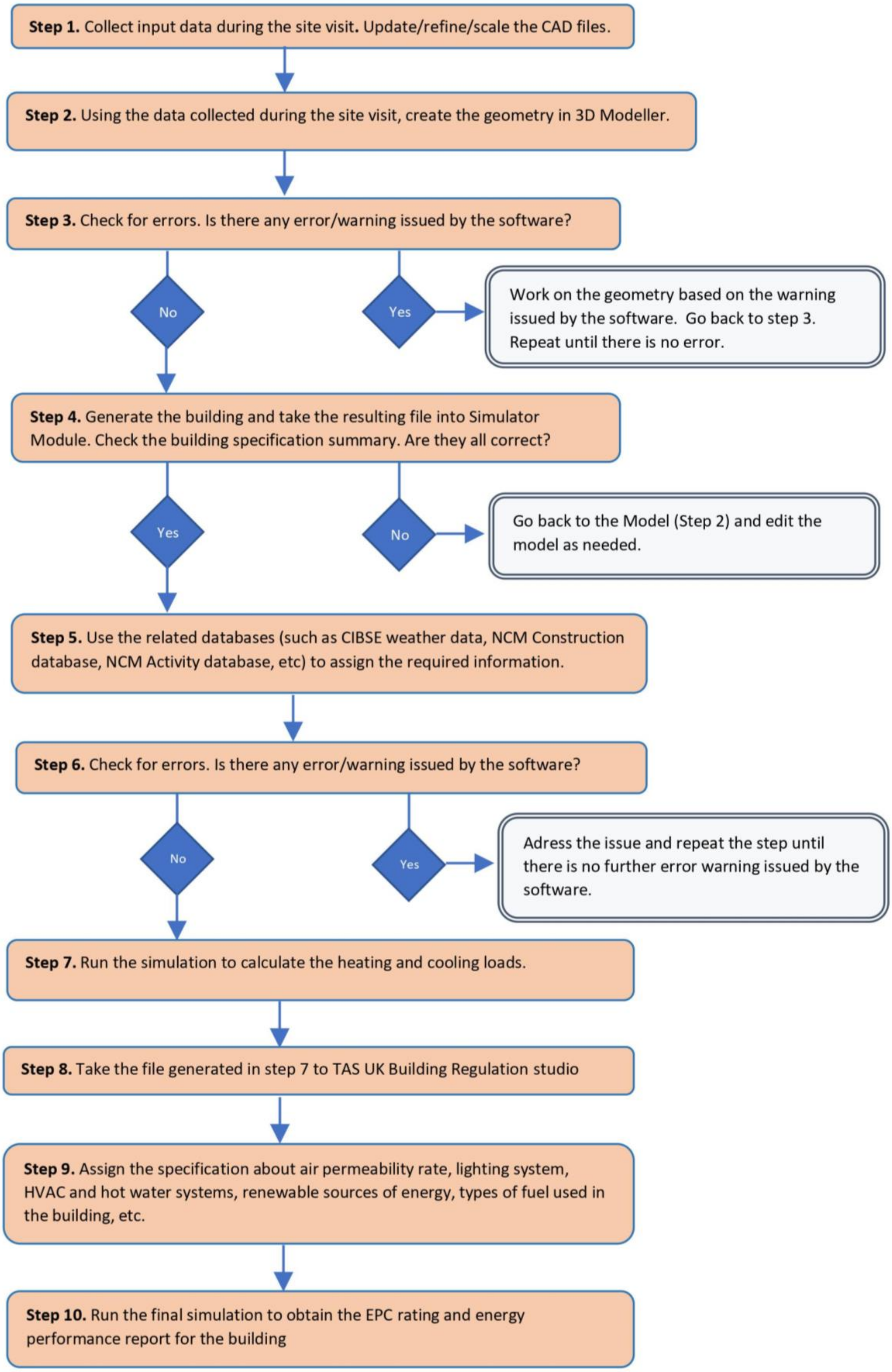


Figure 3.2 Modelling and simulation process in TAS for EPC calculation

3.3.3.3 Modelling assumptions

The assumptions made during the modelling and simulation process follow as below:

- Test Reference Year (TRY) weather files developed by CIBSE are fully adopted without any alterations.
- With regards to the data from the weather files and the building's location and orientation, the automatic simulation of natural ventilation caused by doors, windows, etc. is assumed to be the realistic representation of the airflow in the building.

3.3.4 Simulation output

The simulation results include two main reports:

- A document titled as Energy Performance Certificate, demonstrating the EPC rating of the building and annual CO_2 emission in kg/m^2 per annum.
- A document showing the compliance with the latest UK Building Regulation Part L, through the five criteria, with the first one focusing on comparing the building emission rate (BER) with the target emission rate (TER) (see chapter 2, section 2.2.2.2 for the full list).

The energy consumption for each of the five fixed end-uses are also reported in this document in kWh/m^2. These end-uses are heating, cooling, auxiliary, lighting and DHW, sum of which forms the total annual energy consumption in kWh/m^2, net of any electrical energy displaced by CHP generators, if applicable. TAS also estimate the energy consumption by equipment, however, it does not count towards the total for energy consumption or calculating CO_2 emission.

Following the requirement of comparing the BER with TER, the compliance report compares the energy use in each of the five fixed building services in Actual building with that of the Notional building. If the Actual building's energy consumption for an end use is significantly higher than that of the Notional building, then it can be taken as an initial reminder that the energy efficiency in that specific end use needs to be improved.

3.3.5 Validation of the simulation and a limitation to this study

As discussed in chapter 2, in order to ensure the reliability of simulation results, the data estimated by the software is compared with the measured data. US Department of Energy

(2015) sets guidelines for ensuring the reliability of modelling using two statistical indicators. These two indicators are normalised mean bias error (MBE) and coefficient of variation of the root mean square error (Cv(RMSE)). While the first one shows how close the predicted values are to the measured data, the latter accounts for cancellation error i.e., the impact of positive and negative errors, Equations 3.3 and 3.4.

$$\mathrm{MBE} = \frac{\sum_{i=1}^{Np}(\mathrm{Si}-\mathrm{Mi})}{\sum_{i=1}^{Np}(\mathrm{Mi})} \qquad 3.3$$

$$\mathrm{Cv(RMSE)} = \frac{\sqrt{\frac{\sum_{i=1}^{Np}(\mathrm{Si}-\mathrm{Mi})^{\wedge}2}{Np}}}{Mav} \qquad 3.4$$

Where Si and Mi are estimated and measured data points, respectively. Np is the number of data points at interval p, i.e., $N_{monthly}$ = 12, N_{day} = 365, N_{hour} = 8760. M_{av} is the average of measured data. In the presence of the microclimate for the exact location of the building, the acceptable range for monthly values of MBE and CV(RMSE) are ±5% and 15% respectively (US Department of Energy, 2015).

While data related to microclimate may not be available for many simulations, there can be a challenge of another type with simulations carried out in this study. EPC calculation is from the category of compliance modelling, i.e., it is intended to illustrate adherence to building regulation and it is necessary to follow the specific default values and standard assumptions set by NCM (see chapter 2, sections 2.2.2). Having to follow specific standard guidelines, it is expected that the gap with measured data is increased as suggested by Williamson (2012) and Thompson and colleagues (2021). This suggests that the tight acceptable ranges recommended by the US Department of Energy (2015) may not be achievable. Despite this, it was decided that the statistical indicators illustrated in Equations 3.3 and 3.4 will be used in this work, as there is currently no guideline on how to check the reliability of compliance modelling. However, it is acknowledged that comparing the result of simulation with the operational data is carried out with the purpose of deciding whether the EPC calculation overestimates or underestimates the operational energy consumption of each case, rather than validation.

3.4 Data analysis

Data analysis consists of a range of tasks and activities with the purpose of handling, categorising, interpreting and finally presenting the data in a credible and meaningful way so that patterns can be found, and deep understanding is achieved. The type of data collected in this study is simulation data, generated using the thermal simulation software. The data collected through this process is numeric, therefore, statistical analysis is carried out on the data. The purpose of statistical analysis is to explore the data to find out the potential trends and patterns.

Depending on the specific aims and individual objectives specified for each case investigated in this study, descriptive and inferential statistics are both used which are discussed in full details in their respective chapters.

Chapter 4 Improving the EPC rating of a complying hotel

4.1 Statement of the situation

As mentioned in preceding chapters, with MEES requirement already in place, hotel owners are required to ensure their property meets a minimum EPC rating of band E. While achieving this minimum requirements through cost effective measures may already be challenging, chances are that the regulation becomes stricter in near future, raising the compliance minimum as high as band B by April 2030 (DBEIS, 2019). Therefore, a hotel that meets the current requirement, may fail to do so when stricter measures are introduced.

In this chapter, Hilton Reading is studied. As the building was finished in 2009 - signalling that the planning and approval phases had been done a few years earlier - it is assumed that the building complies with the UK Building Regulation Part L 2006. Therefore, it is expected that the building meets the current MEES requirement of EPC rating. With what was elaborated about stricter requirements, the possibility of improving its EPC to a better band is investigated in this chapter. This will be pursued through different approaches. The building has a high window to wall ratio - 0.6 - meaning that significant part of the external surfaces in this building is covered with transparent elements. Therefore, the possibility of improving the EPC through improving the thermal performance of its transparent elements will be studied. Following from the glazing elements, the next point of focus will be on incorporating low/zero carbon technologies.

The choice of measures for improving the energy performance of the glazing for this building was carried out according to one of the following:

- Applying the measure does not cause major disruption to the hotel's typical activities.
- The glazing elements/films are commercially available in the UK.

Therefore, for the first part, improving the EPC rating of the building is pursued through applying a specific type of Low-*E* window film (elaborated in detail in the next section), which is then compared against another scenario in which Low-*E* coated, Argon-filled window units are installed in the building from the beginning - as is the case with many new builds in the UK. The low-*E* characteristic of this glazing unit is different from what is used in the film.

Furthermore, as windows with U-values larger than 1.0 W/m^2.K can still contribute to a huge heat loss (Cuce, 2018), an Argon-filled triple-layered glazing with a U-value below 1.0 is also chosen and EPC calculation is done for it. In the next rounds of simulation, improving the EPC through low/zero carbon technologies such as heat pumps and combined heat and power (CHP) is investigated.

4.2 Building description

4.2.1 Building geometry and fabric

The building studied in this chapter, Hilton Reading, has a total floor area of 12,360 m^2. The ground floor encompasses areas such as the reception, lobby, restaurant, hall, administrative offices and meeting rooms, and laundry. The hotel also has a swimming pool and a gym located on the ground floor level. First, second, and third floors accommodate 210 ensuite guest rooms. The building façade is mostly covered with curtain walls; double-glazed units comprising of two 4-mm clear panes with a 50 mm air-filled gap. As mentioned, the construction work on this building was finished in 2009, therefore it is assumed that it complies with the UK Building Regulation Part L 2006. Typical floor plan and building geometries are shown in Figures 4.1 and 4.2, respectively.

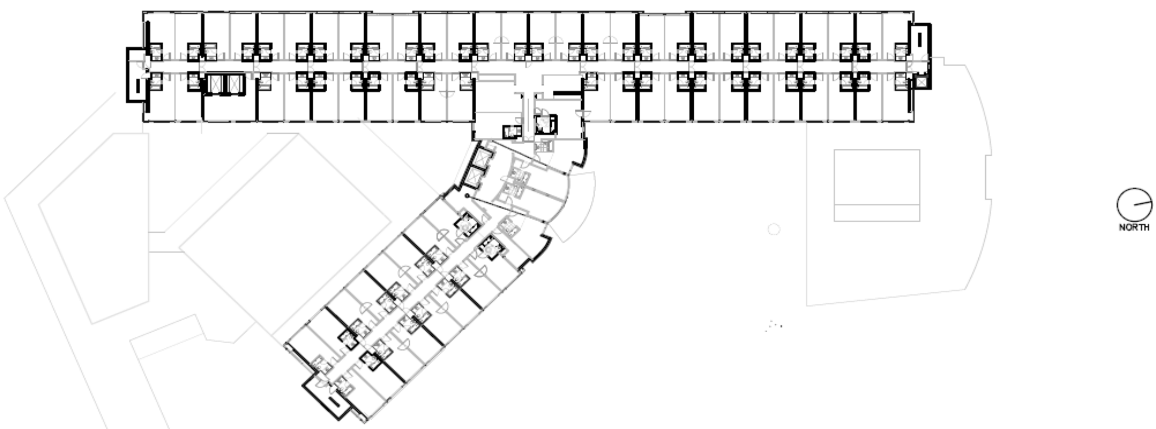
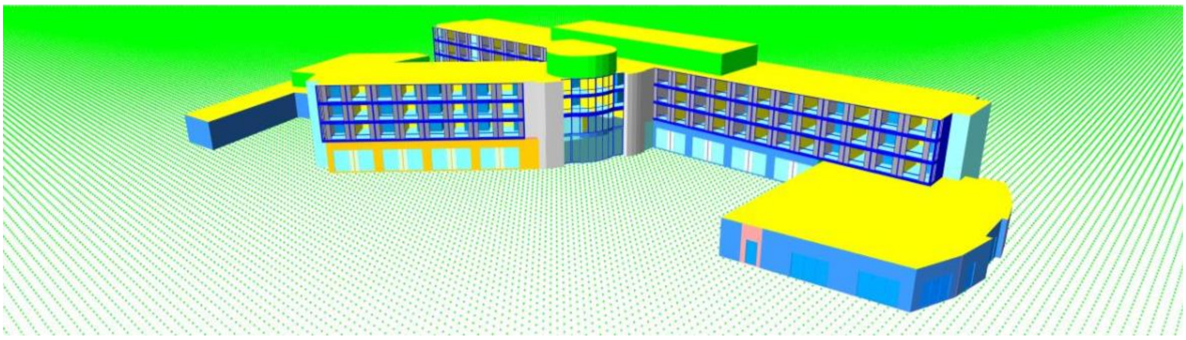
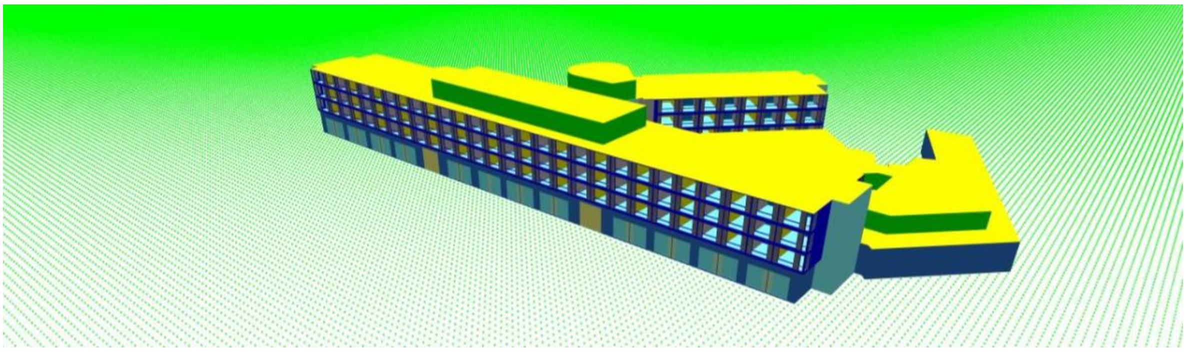


Figure 4.1 Typical floor plan.



(a) Front View.



(b) Rear View

Figure 4.2 Views to the building geometry

4.2.2 Building services

The building is sealed and fully air conditioned, meaning that heating, cooling, and mechanical ventilation is provided throughout the hotel. Fan coil units (FCU)s, connected to the main air handling units (AHU)s on the roof, carry the air conditioning services to every space in the hotel. The AHUs are supported by gas-fired boilers and chillers. The boilers are also responsible for providing the DHW. The hotel also has an active restaurant for which the number of food covers is high. The kitchen cookers supplying food for the catering activities use natural gas.

4.3 Modelling assumptions

The weather file used for the simulation is London TRY, as it is the closest station among the files available from CIBSE (see chapter 3, section 3.3.3.2 for information on why TRY files should be used). According to London TRY, the minimum and maximum outdoor temperatures are −3.2°C and 30.7°C, occurring on March 2nd and July 14th, respectively. Figure 4.3 illustrates the hourly outdoor temperatures in this weather file.

Based on the information collected during the site visit and the common constructions at the time of construction, the building fabric specifications are shown in Table 4.1.

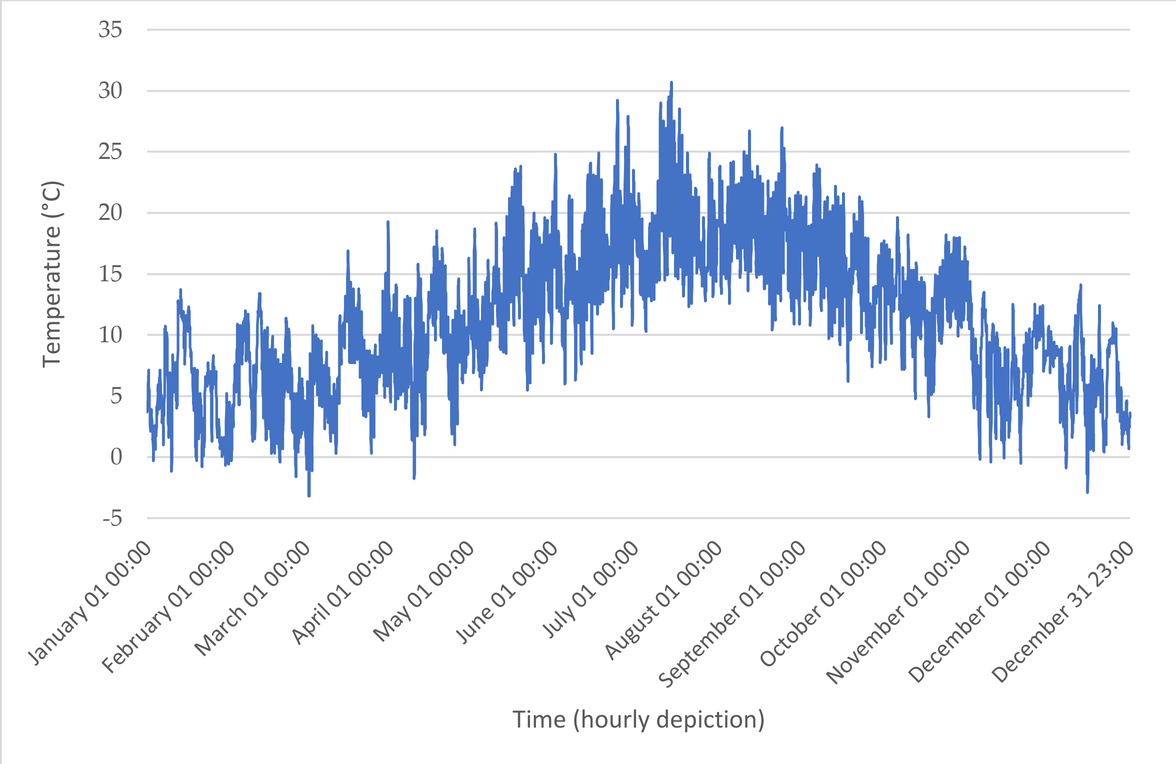


Figure 4.3 Hourly outdoor temperature in London TRY weather file, reproduced from the weather file by (CIBSE, 2017b)

Table 4.1 Building fabric specification considered for the simulation.

Building element	Construction	Area-weighted average U-value (W/m²K)
External wall	Solid wall (E&W) Part L 2002, consisting of concrete blocks, 25 mm of air layer and polyurethane (PUR)	0.35
Ground floor	Solid floor (E&W) Part L 2002, consisting of clay underfloor, stone chipping, concrete slab, and polyurethane (PUR)	0.25
Roof	Flat roof (E&W) Part L 2002, consisting of stone chipping, extruded polystyrene (EPS) and concrete slab	0.25
Curtain wall	Double-layered glazing (4-50-4), air filled	2.12

Metal frame with thermal break and thermally improved spacer	5.35

The air permeability rate of the building is considered as 10 $m^3/h.m^2$ @50 Pa. Air permeability is an indicator of how airtight a building is and is defined as "*air leakage rate per hour per square meter of envelope area at the test reference pressure differential of 50 Pascals*" (UK Government, 2010, p.28)

4.4 Choice of measures for improving the EPC

4.4.1 Type of Low-*E* window film and its position

The Low-*E* window film chosen for this study is a product of 3M company (3M, 2019). The product comes with the commercial name of Thinsulate Climate Control 75 and a transparent look. It also offers improvement in Low-*E* characteristics compared to similar products. According to the manufacturer, Thinsulate coating is suitable for both winter and summer time. Table 4.2 shows the specification of 3M Thinsulate Climate Control film compared with those of solar control films from the same manufacturer; Sun Control Prestige 70 and 40 Exterior.

Table 4.2 Thinsulate and Prestige films specification

Type of window film	Visible light reflected (interior)	Visible light Reflected (exterior)	Visible light transmitted	*G-value
Thinsulate CC 75	17%	21%	66%	0.51
Prestige 70 EXT	14%	12%	63%	0.39
Prestige 40 EXT	13%	7%	37%	0.29

*G-value is an indicator of how well the glass/coating transmit the heat from the sun and it can be a maximum of 1.0 (or 100%).

Type of window film	UV Block	Heat gain reduction	Heat loss reduction	Emissivity
Thinsulate CC 75	99.9	27	40	0.15
Prestige 70 EXT	99.9	45	-	0.84
Prestige 40 EXT	99.9	59	-	0.84

As observed, apart from difference in behaviour towards the visible light, there are also noticeable differences between Thinsulate and Sun Control films for the *G*-value, heat gain/loss reductions, and emissivity. Based on this information, the Thinsulate coating lets more solar gain through the glazing compared to the sun control films. Therefore, the sun control films perform better in the summer. Another important factor to consider is that the sun control films do not contribute towards the heat loss reductions, while the Thinsulate can reduce the heat loss through glazing, favourable for winters. This quality is achieved through a significantly lower emissivity rate for the Thinsulate film. As the hotel is located in a heating-dominant climate, the improved performance in heat loss reductions is of higher importance in energy saving field. A lower emissivity rate means that the heating energy from the indoor space - in the form of infrared radiation - cannot pass through the film, therefore, reduction in heat loss is achieved.

The surface that the coating is applied on can have an impact on thermal performance of the glazing and the amount of energy saving. Ye *et al.* (2013) are of the idea that the best performance for a single layered window with Low-*E* coating is achieved when the coating is applied on the inner surface. In the study done by Chow, Li and Lin (2010) in a cooling-dominant climate, applying Low-*E* coatings to the inner surface of the external layer in a double glazed window resulted in up to 48% reduction in heat gain compared to a single clear glass, although the surface temperature of the window exceeded 40°C, which is not a negligible issue. Interestingly, when the coating was applied on the outer surface of the external glazing, the reductions in heat gain and the surface temperature of the glazing were both decreased, compared to the first round (Chow, Li and Lin, 2010). However, it should be noted that many films and coatings should be kept from external environment or else, their lifetime becomes shorter.

Figure 4.4 shows all the possible alternatives for positioning a coating on a double-glazed window unit. Thinsulate films cannot be exposed to outdoor weather conditions, which means ruling out alternative 1 of Figure 4.4. When a double-glazed unit is designed and manufactured with Low-*E* quality from the start, the Low-*E* layer will be applied within the gap between the two windowpanes, alternatives 2 or 3. But when the coating is applied on an existing window, it is usually not possible to have it positioned on either of the alternatives 2 or 3. Therefore, alternative 4 of Figure 4.4 is considered as the positioning condition for applying Thinsulate films on the windows.

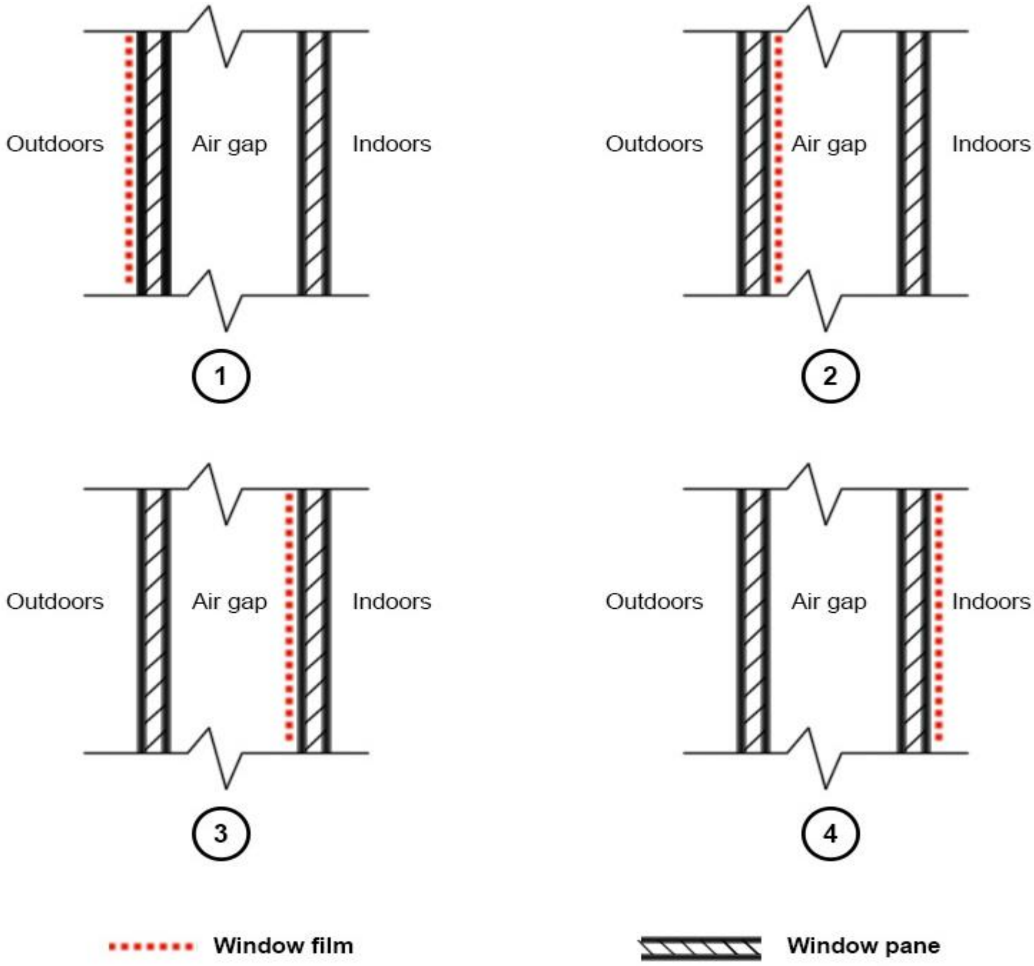


Figure 4.4 Different options for positioning a window film.

4.4.2 Using the opportunity of electricity grid going green: heat pumps

In recent years, the UK electricity grid has been on the path to become greener. This means that compared to the past, larger share of the total generated electricity comes from renewable and nuclear sources while there has been a considerable decrease in burning fossil fuels for generating electricity, Figure 4.5. The UK has a varied mix of renewable technologies when it comes to electricity generation such as biomass, wind, solar photovoltaics, hydro and shoreline wave (DBEIS, 2020). According to the Digest of UK Energy Statistics, since 2010, the use of fossil fuel for electricity generation has been cut down by 59%, while during the same period the share of renewables has increased fivefold. In 2019, 37.1% of total electricity generated in the UK came from renewables (DBEIS, 2020), This number amounted to 43.1%

in 2020 and for the first time, the share of renewables was more than the fossil fuels, which was 37.7% (DBEIS, 2021). The change in the fuel mix consumed in the UK power stations over the years has resulted in reductions of emission conversion factors. Based on the data from the Government (DBEIS and DEFRA, 2019, 2020, 2021), the electricity emission factor in 2019, 2020 and 2021 are 0.2556, 0.23314 and 0.21233 kgCO_2e/kWh, respectively.

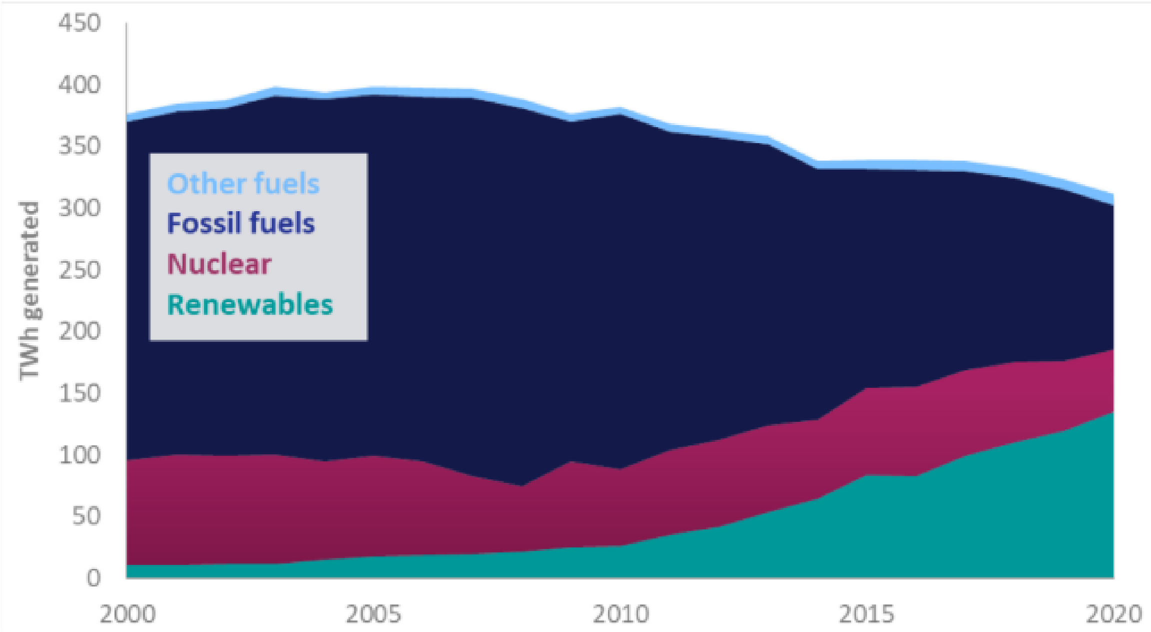


Figure 4.5 Electricity generation by fuel, 2000–2020 (DBEIS, 2021)

With the increase in the share of renewables in electricity generation, calls for electrification of the UK' heating infrastructure are on the rise. Combined with the benefits associated with low/zero carbon technologies, the idea of using heat pumps for space heating purposes was prompted. Application of heat pumps in hotels has been discussed in many studies, examples include Lam and Chan (2003), Chan *et al.* (2013), Michopoulos *et al.* (2017) and Smitt *et al.* (2021).

A heat pump is a mechanical system that transfers the thermal energy or heat from the source – at a lower temperature – to another location at a higher temperature (ASHRAE, 2004). To put it in a nutshell, a heat pump, removes heat from a cold place to a warm one, through refrigeration cycle. Rather than generating heat, a heat pump transfers it using electricity. This heat is freely available from the ground, water, or air. Heat pumps can deliver up to 3 to 4 kW of heat for 1 kW of electricity they consume, resulting in much higher efficiencies than traditional heating systems. For example, ground source heat pumps can reach efficiencies as high as 500%, which is expressed by Coefficient of Performance (CoP) of 5.

For the practicality and the fact due to lack of space, installing and using ground source heat pumps in an existing hotel of this size may not be possible, an air source heat pump (ASHP) is used for this hotel.

4.4.3 Implementing the CHP system for the simulation model

4.4.3.1 Choosing the heat and power output for the CHP system

Following the discussion about the importance of proper sizing in chapter 2 (see section 2.4.3), the CHP for this building will be sized to deliver a constant base heat load. The base heat load will be decided from the monthly heat consumption simulated by the software. The reason for looking at the simulated data rather than the measured data is that the measured data shows all the monthly gas consumption, regardless of whether it is for heating/DHW purposes or kitchen cookers and catering activities. Therefore, it was not possible to accurately find the building's base heat load through measured data.

Upon finding the month with the lowest amount of thermal energy consumption, the hourly heat consumption is checked to obtain the base value. According to Good Practice Guide 588 by CIBSE on CHP system (Actione Energy, 2004), it is possible to use the monthly heat consumption for identifying the base heat load, but hourly data are preferred, for higher accuracy (Actione Energy, 2004). When the base heat load from the model's hourly data is selected, the typical/commercially available CHP systems are checked. By finding a CHP system whose thermal output matches the base heat load of the building, the electric output of the system will be defined.

4.4.3.2 Data needed for adding a CHP system to TAS Studio

In this stage, based on the heat to power ratio and further information such as the overall CHP efficiency, the software sizes the CHP system. When implementing a CHP system in TAS, it should be specified whether the system's priority is on DHW or space heating. It is generally accepted that a CHP should always be running to derive a benefit. With the NCM Activity database assigning a continuous demand for DHW in the hotels, setting the priority to DHW will guarantee this.

Another important factor is the size fraction. Size fraction is the proportion of the "peak" load that will be met by the CHP system. If the CHP is to be sized on the space heating demand, then the size fraction will be the proportion of the peak space heating demand (not annual demand) met by the CHP. If the CHP is to be sized on the DHW demand, then the size fraction will be the proportion of the peak DHW demand met by the CHP.

4.5 Measured data for the existing hotel

The hotel's measured monthly energy consumption during the period 2010 - 2018 is illustrated in Figure 4.6. As expected, the energy consumption fluctuates throughout the year and also from one year to another.

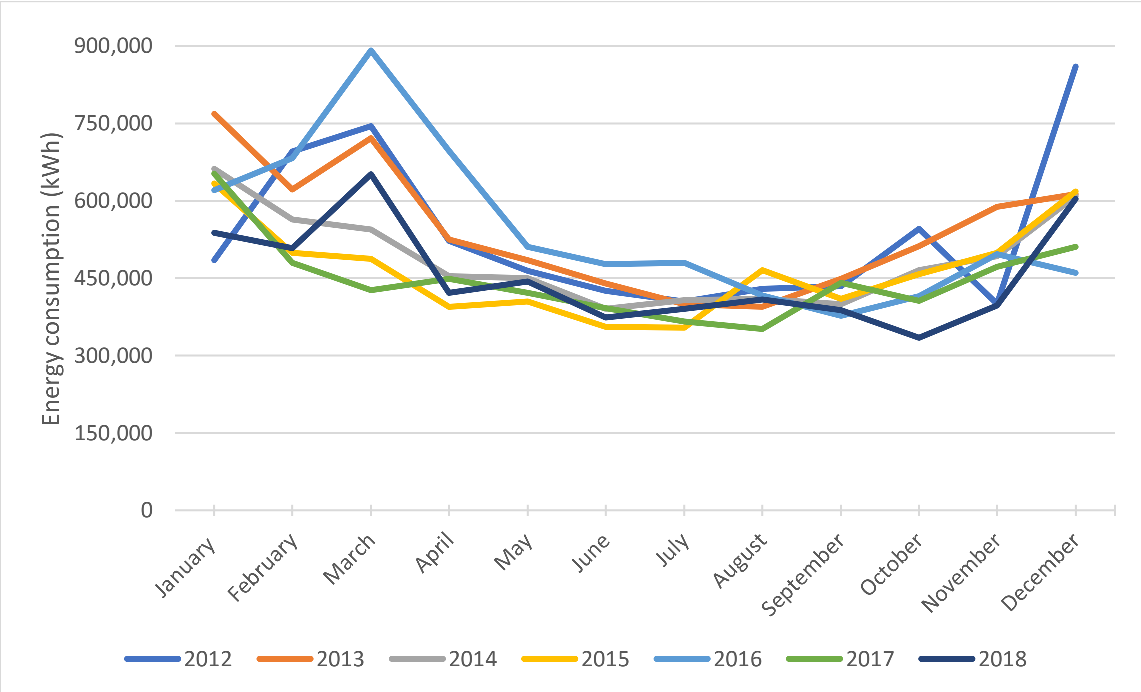


Figure 4.6 Measured energy consumption data for Hilton Reading (2012-2018)

As shown, the energy consumption of the hotel tends to be lower during the warmer times of the year, i.e., from May to September. This is justifiable by the fact that the hotel is located in a heating dominant climate, therefore its energy consumption increases during the colder times of the year, signalling that the outdoor weather situation can be very impactful on the energy consumption of this hotel and its fluctuations. Further discussion on how occupancy rates and outdoor weather temperature affect the monthly energy consumption are discussed in detail in chapter 6.

4.6 Simulation results

4.6.1 Baseline model

By carrying out the EPC calculation in TAS, the building in its current condition - which forms the baseline model - receives the EPC band of C with the asset rating of 51. Based on this, the annual energy consumption and CO_2 emission of the building are calculated as 310.71 kWh/m^2 and 93.42 kg/m^2, respectively. It should be noted that as explained, the energy used by equipment, although calculated by the software, does not count towards the total for consumption or calculating emissions. Therefore, the two numbers mentioned in the lines above, are excluding the share from equipment end-use. The equipment end-use entails the unregulated energy consumption in a building. Examples in a hotel include but are not limited to portable/task lighting devices, computer, monitors and printers, coffee machine and mini bars, vending machines and lifts.

The breakdown of the annual energy consumption is shown in Figure 4.7. The shares are estimated by TAS using the building characteristics and NCM Activity database profiles. In order to avoid ending up with significantly overestimated numbers, the share of equipment end-use is also demonstrated in the pie chart. As shown in the graph, the estimated share of DHW is more than half of the total energy consumption. In chapter 6, the question as to whether this reflects the reality is explored in detail.

Despite being in a heating-dominant weather condition, the share of heating end-use is less than 10%. The smaller share of the heating end-use in this hotel – compared to the other two hotels simulated with the same weather file, discussed in upcoming chapters – is due to lower thermal transmittance of building elements i.e., U-values and the building fabric being less leaky. These characteristics are achieved as a result of compliance with more recent Building Regulations limiting U-values – compare Table 4.1 and Table 5.1 in chapter 5 as an example – and reduced air permeability rates. As full air conditioning takes place in the building i.e., heating, cooling and mechanical ventilation, the share of auxiliary end-use is also remarkable. The auxiliary end use accounts for the electricity used by the fans and pumps in the HVAC systems.

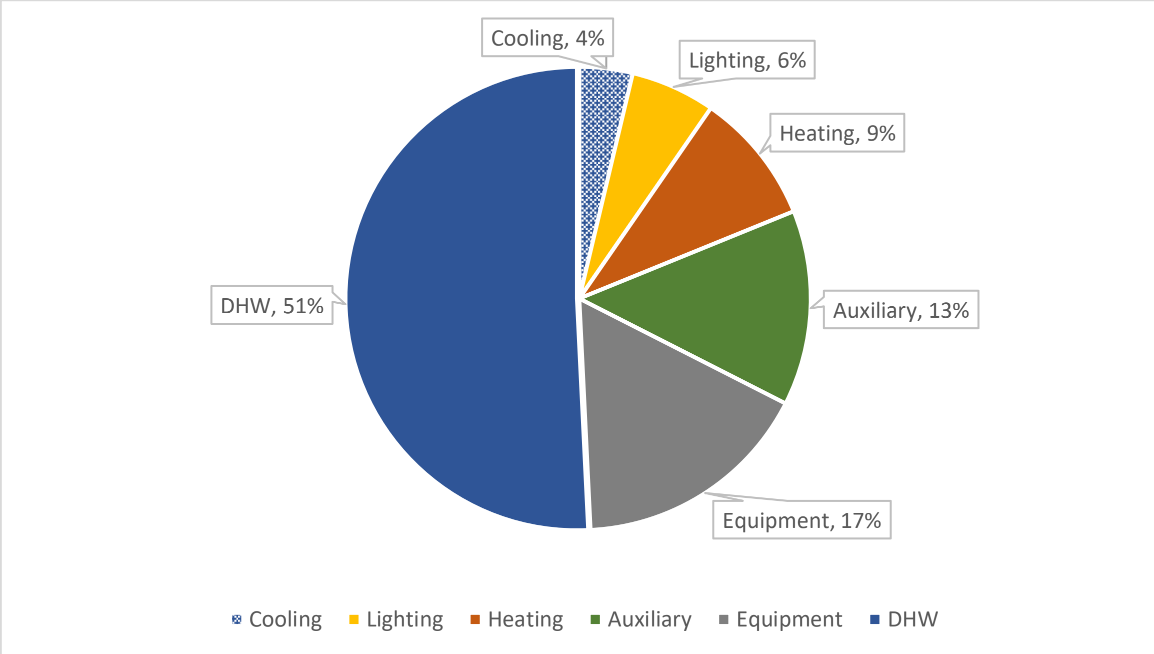


Figure 4.7 Share of end uses in annual estimated energy consumption.

4.6.2 Comparing the simulated data with the measured data

The energy consumption predicted by the software is compared with the measured data in Figure 4.8. Although monthly measured data is available from previous years, but for the purpose of comparison, it is best to focus on recent years as they are closest to the current situation in terms of any changes to the building and its services. From the graphs in Figure 4.8 it is understood that the simulated data (yellow dashed line) is an underestimation of the monthly energy consumption. While every effort was made to ensure that the model replicates the actual building in every aspects, the role of occupant behaviour and default values in increasing the gap between simulated and measured data should not be overlooked.

Furthermore, as it was discussed in chapter 3 (see section 3.3), the EPC calculation is a compliance modelling, therefore it doesn't consider the unregulated energy use such as catering. Interestingly, in this hotel, the number of food covers is almost significant. Although NCM Activity database profiles for kitchens is inclusive of the environmental energy consumption for catering activities e.g., the lighting needed for cooking, but it does not include the energy used for food preparation. If the operational energy consumption for catering activities is added to the simulation, the estimated monthly energy consumption arises to the amounts shown with the blue dashed line in Figure 4.8. It should be mentioned that the operational energy consumption for catering added to the simulation is calculated based on the guideline by CIBSE (2009) - 2.54 kWh of gas and 1.46 kWh of electricity per meal served in the hotel - and the average numbers of food covers for the hotel during 2016–2018.

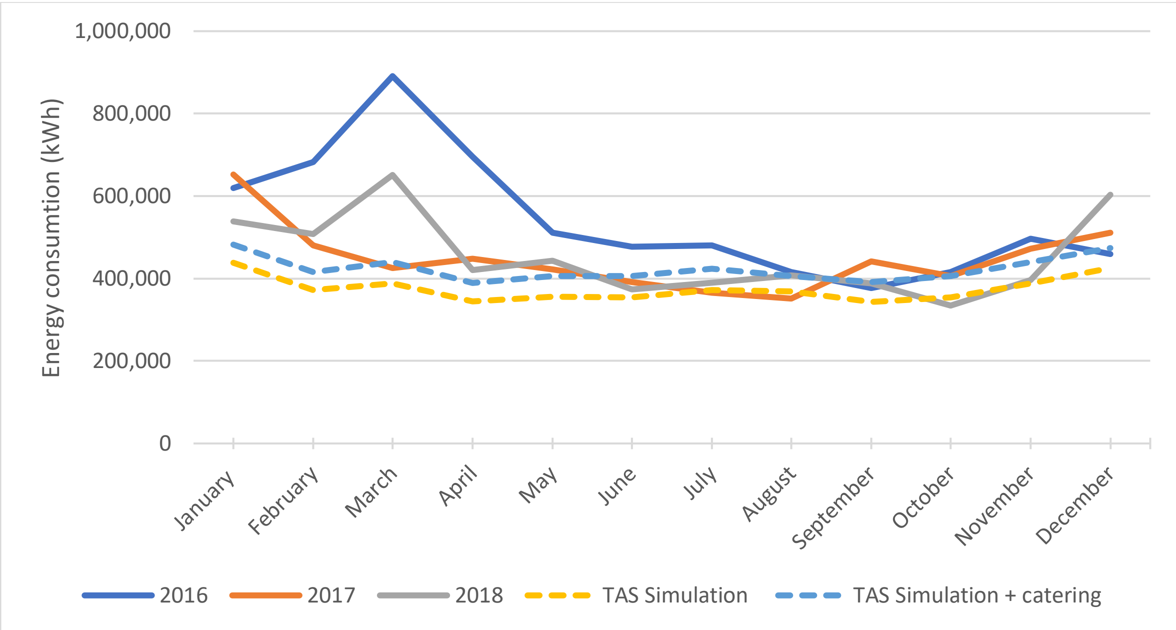


Figure 4.8 Comparing the simulation result (baseline model) with the measured data

Another point worthy of mention in Figure 4.8 is that the graphs for measured data undergo more fluctuations compared to that of the estimated data. Also, occasionally, extreme readings are recorded such as those occurring in March 2016 or March 2018, whereas the graph for estimated consumption follows a more moderate pattern, without any extreme point. This can be explained by the following points:

- The type of weather file used for the EPC calculation is a TRY file. As explained in chapter 3, TRY file is of a normalised nature and excluding of any extreme weather situations. In real situation, undergoing extreme weather situation – e.g., a specifically cold winter month or a very hot summer month – can increase the energy consumption, causing an extreme reading for that month.

- Some of the energy intensive end-uses such as DHW is dependent on the floor area covered by the corresponding activity. For example, for guest rooms it is 13.12 litre per calendar day per square meter of floor area covered by the guest room activity in the hotel. As this area remains intact throughout the year, the amount of DHW load is only affected by the number of days in each calendar months. Therefore, the amount of energy consumption for DHW fluctuates very slightly over the course of one year.

The two statistical indicators introduced in chapter 3 are used here as a means of comparing the simulated and the measured energy consumption data, Table 4.3. Again, given the negative values for MBE, it can be concluded that the EPC analysis for this hotel in its baseline condition is an underestimation of its actual/measured energy consumption.

Table 4.3 Statistical indicators for estimated data (baseline model) when compared with measured data

	2016	2017	2018
MBE	-22.14%	-6.35%	-6.90%
Cv (RMSE)	34.0%	14.1%	18.46%

4.6.3 Retrofitted models with improved glazing elements

4.6.3.1 EPC results

The results of improving the thermal performance of glazing elements are presented in this section. To avoid confusion, in this section following models are discussed:

- **Baseline model:** Hotel building in its existing state.
- **Model with Thinsulate film (TF):** Model with Thinsulate film applied as a retrofitting measure on the internal surface of the inner windowpane (alternative 4 of Figure 4.4):
    - 4 mm clear glass with Thinsulate 75 film
    - 50 mm air gap
    - 4 mm clear glass
- **Model with double glazing, Low-*E* coating, and Argon-filled gap (DLAr):** A commercially available double glazed, Argon-filled unit, with factory-built Low-*E* characteristics. In this unit, the Low-*E* coating is on the external pane, facing the gap:

- 4 mm clear glass
- 20 mm Argon-filled gap
- 4 mm glass with Low-*E* coating

- **Model with triple glazing, Low-*E* coatings, and triple glazed unit (TLAr):** A commercially available triple glazed, Argon-filled unit which is built in the factory setting with Low-*E* coatings on its middle and external panes.
  - 4 mm clear glass
  - 12 mm Argon-filled gap
  - 4 mm glass with Low-*E* coating
  - 12 mm Argon-filled gap
  - 4 mm glass with Low-*E* coating

Table 4.4 shows the EPC rating, energy consumption and CO_2 emission for all the models. In line with the EPC procedure, the numbers for energy consumption and CO_2 emission rates are inclusive of the fixed building services. The equipment end-use has <u>not</u> been counted towards the total in either of the two parameters.

Table 4.4 EPC rating and emission rates for the three models

	EPC rating	**Energy consumption (kWh/m^2)**	**CO_2 emission (kg/m^2 per year)**
Baseline	C (51)	310.71	93.42
TF	B (46)	297.47	86.9
DLAr	B (46)	291.39	86.94
TLAr	B (45)	283.19	83.6

As expected, all the retrofitted models have achieved reduction in CO_2 emission compared to the baseline model. As the baseline model has a borderline AR – 51 – even the small improvement in the ARs of the retrofitted models results in EPC band change, from C to B. Had the baseline model featured a higher AR, changes in the retrofitted models might not have resulted in an improved EPC band.

Looking at the third and fourth columns in Table 4.4, an important point is noticed. By using double layered, low-*E* coated, Argon-filled glazing, i.e., in the DLAr model, the energy consumption and CO_2 emission are reduced by 6.22% and 6.94%, respectively, compared to the baseline model. On the other hand, in TF model, where Thinsulate 75 film is used, compared to the baseline model, reductions of 4.26% and 6.98% are achieved in energy consumption and CO_2 emission, respectively. This means that despite a smaller reduction in energy consumption, the TF model archives similar levels of emission reduction as the DLAr model. The reason for this is explained in the following section.

4.6.3.2 Energy consumption Vs. CO_2 emission

The reason for achieving similar emission reductions despite having different levels of energy consumption in TF and DLAr models can be explained by focusing on the end-uses which undergone a change. These end-uses are heating, cooling, and auxiliary. Figure 4.9 illustrates the energy use for each of these end-uses.

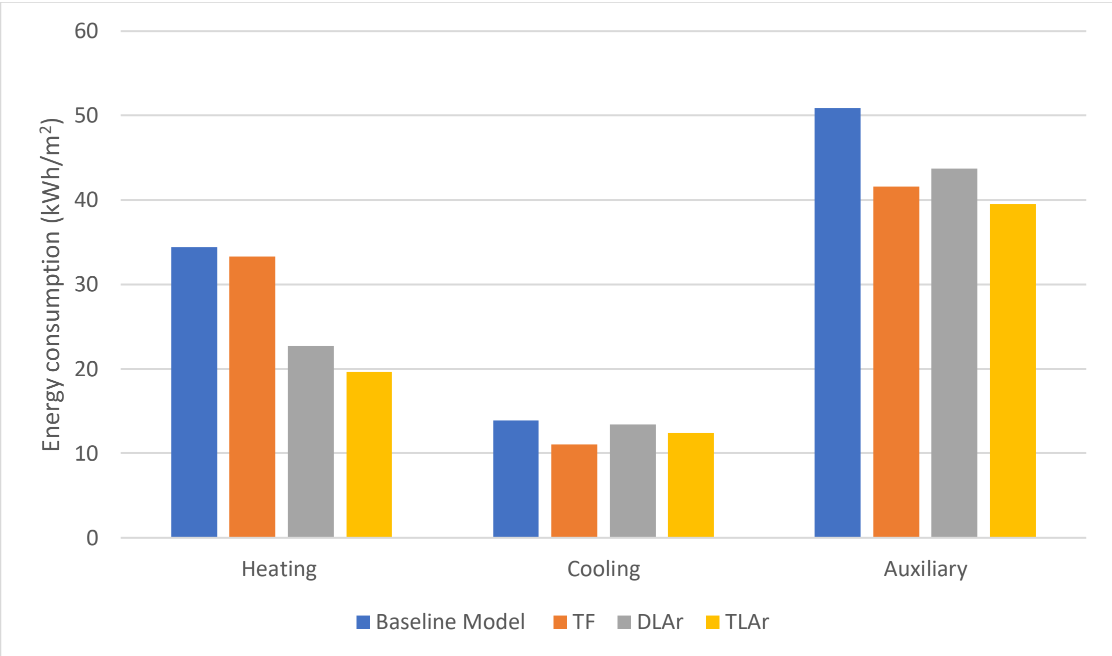


Figure 4.9 Energy consumption for the end-uses affected by the retrofit

As shown, reduction in heating end-use in DLAr model is much higher than TF model. On the other hand, the TF model provides more saving in cooling and auxiliary end-uses, compared to the DLAr. In this hotel, heating is provided through natural gas while electricity is used for cooling and auxiliary end-uses. The carbon factor - a coefficient which allows to convert activity data into GHG emission - for electricity is much higher than that of natural gas, 0.519 kg/kWh and 0.216 kg/kWh, respectively. Therefore, the TF model's better performance cooling and auxiliary end-uses balances the DLAr model's better performance in heating end use in terms of CO_2 emission.

(Note: the carbon factors mentioned here are different from the emission conversion factors by the UK Government mentioned in section 4.4.2. The carbon factors are assigned by NCM and therefore, mandatory to follow. NCM updates them every few years. At the time of writing this work – September 2021 – the numbers are as above).

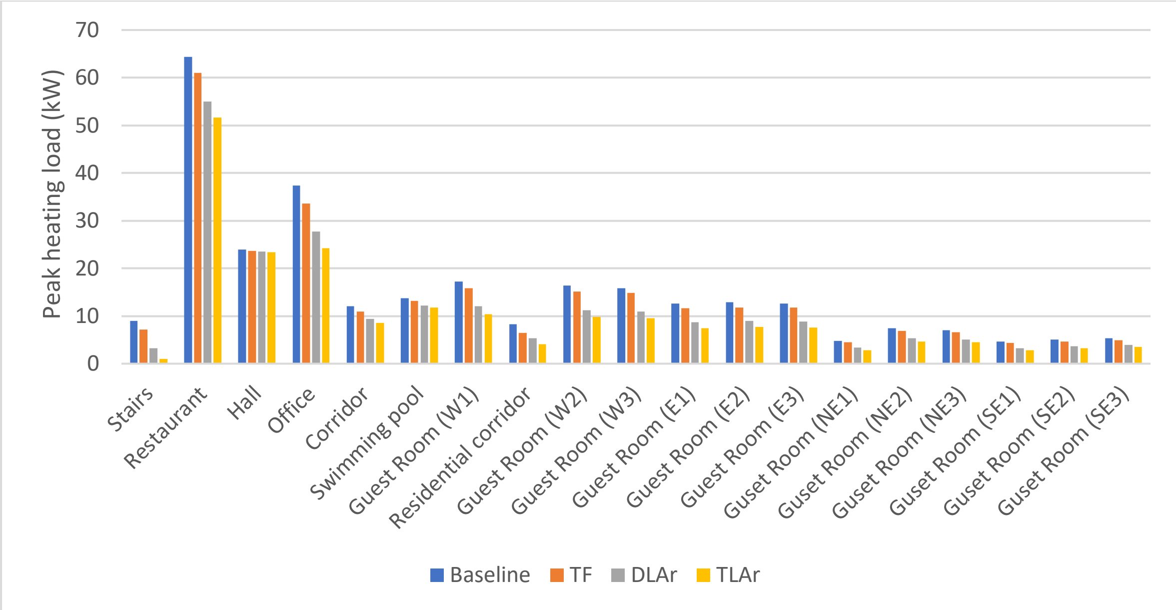
From Figure 4.9 it is understood that Thinsulate 75 film reduces the emission from both heating and cooling end-uses, an advantage over the company's sun control films introduced in Table 4.2. Despite the savings in both end-uses, it is obvious that the Thinsulate 75 film has a better performance in reducing the cooling energy use. On the contrary, in the DLAr model, higher savings in heating energy use is achieved, rather than the cooling, which can be due to the following:

- An overall lower U-value (1.306 $W/m^2.K$)
- The position of Low-*E* coating
- The smaller gap between the layers.

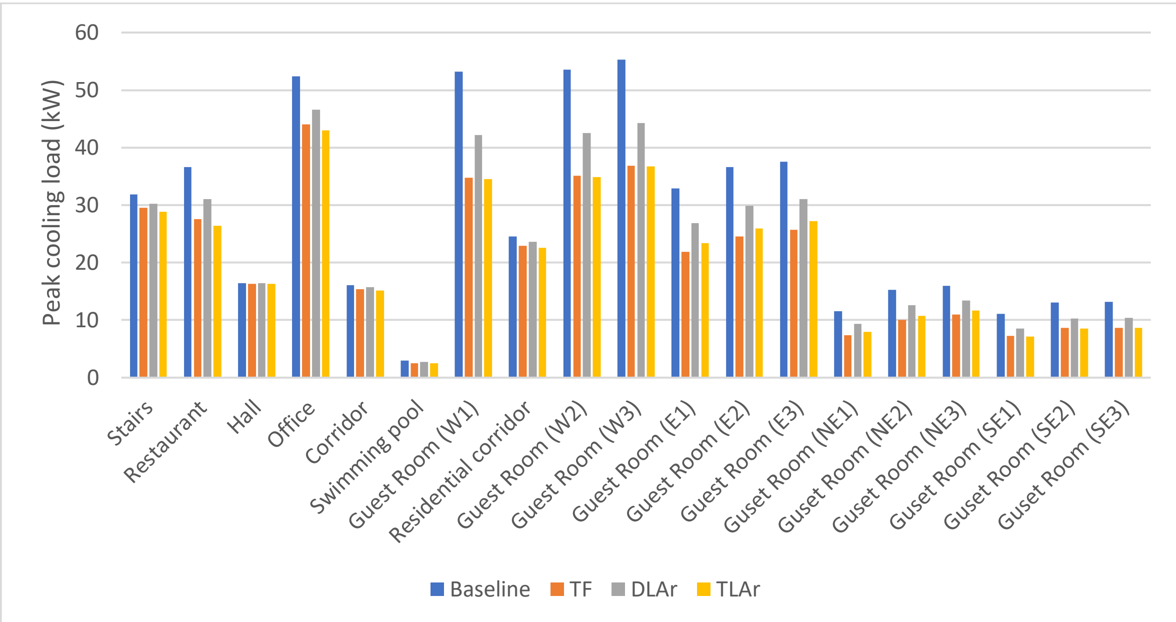
Among all the retrofitted measures, the model with triple glazing, i.e., TLAr model provides the best result. However, it should not be ignored that this improved performance comes at a high cost, as triple glazed windows are known to be very costly.

4.6.3.3 Impact on the Auxiliary energy use

The maximum reduction – both in energy consumption and emission rates - among all the three retrofitted models occurs in auxiliary end-use (see Figure 4.9), with the numbers being 18.27% for TF model, 14.09% for DLAr model and 22.21% for TLAr model. Auxiliary energy in the EPC calculations refers to the energy used by fans, pumps and controls of a system regardless of whether it was used for heating, cooling or ventilation (DCLG, 2015). It is beyond the scope of this work to go through all the steps for calculating the auxiliary energy use, however, it can be briefly mentioned that auxiliary energy "*is the product of auxiliary power density and annual hours of operation of the heating system from the activity database. The auxiliary power density is the sum of the pump and fan power density*" (DCLG, 2015, p. 89). The pump power density (W/m^2) is a single number which depends on the building's HVAC system. The energy used by pumps remains the same for all the models. Without going into any details, it should be mentioned that the fan power density for this building depends on the peak heating <u>or</u> cooling load – the greater of the two. Figure 4.10 shows the peak loads for some of the main zones in the building. Comparing the peak loads in Figure 4.10, it is understood that for most zones, the peak cooling load is greater than the peak heating load.



(a) Peak heating loads



(b) Peak cooling loads

Figure 4.10 Peak heating and cooling loads

As shown in Figure 4.10.b, the difference between the peak cooling loads in baseline model and retrofitted models are quite considerable, especially for TF and TLAr models. Therefore, the savings in the auxiliary energy use is justified.

4.6.4 Retrofitted models with ASHP

The impact of adding ASHP on the EPC rating of the hotel is shown in Table 4.5. the efficiency of the heat pump is 300% equal to CoP=3.

Table 4.5 EPC rating and emission rates for models with ASHP

Model	EPC rating	Energy consumption (kWh/m^2)	CO_2 emission (kg/m^2)
Baseline	C (51)	310.71	93.42
ASHP (for space heating)	B (49)	286.74	91.4
ASHP (for space heating) + **Electric heater** (for DHW)	D (76)	269.7	139.97

By using the ASHP for space heating and leaving the existing gas-fired boilers to meet the demand for DHW, a small reduction of 2.2% is achieved in CO_2 emission. However, as explained in previous section, with the borderline AR of the baseline model, i.e., 51, even the marginal improvement in the AR of the model with ASHP resulted in the EPC rating going from band C to band B. Failing to make a significant improvement in the EPC rating despite increasing the heating efficiency from 91% to 300% is caused by relatively small heating demand in this building. See section 4.6.1 for more details on this matter. This suggests that considerable improvements in the EPC rating may not be achieved if the retrofitting measure is aimed at an end-use with insignificant share of contribution to overall energy consumption and/or emission rate.

With the high share of DHW end-use in the EPC estimation for this hotel, the impact of using electric heaters for DHW alongside the heat pumps for space heating was investigated. The choice of electric heaters for DHW was based on their higher efficiencies, compared to the gas-fired boilers. Electric heaters can reach efficiency of 100%. However, they are expensive to run. The result of adding electric heaters for DHW is also shown in Table 4.5.

As seen, despite 13.2% reduction in energy consumption compared to the baseline model, the CO_2 emission has undergone an increase of 49.8%, compared to the baseline model. This results in the EPC rating to drop to band D. A worsened EPC rating despite reductions in the energy consumption is caused again by the difference in carbon factors for gas and electricity. Now, instead of natural gas with carbon factor of 0.216 kg/kWh, grid electricity with carbon factor of 0.519 kg/kWh is used to meet the DHW demands, which is the most energy intensive end-use among the five.

This is an example of situations in which reducing the energy consumption does not necessarily result in emission reduction.

4.6.5 Retrofitted model with CHP system

4.6.5.1 The base heat loads

As explained, in order to size a CHP system, the base heat load of the building should be determined. While it is possible to use the monthly data, selecting the base heat load from the hourly data increases the accuracy of the sizing.

Looking at the hourly heat consumption obtained from TAS, the base hourly heat consumption for the hotel is 260 kWh. Based on this, the CHP system is sized as a 210 kW_e unit. This is selected by examining the existing CHP unit ratings and matching their thermal output (Shenton Group, 2021) to the base heat load of the building. The overall efficiency of the CHP system and heat to power ratio are 80% and 1.18, respectively. After running the simulation for this CHP system, smaller and larger sized systems are also simulated to see the impact on the CO_2 emission and the EPC rating.

4.6.5.2 EPC results

As mentioned, it is accepted that the CHP should be running constantly to provide benefits. As there are times especially over the summer months, when the heating demand is zero, therefore the simulation tool was assigned to size the CHP based on DHW load. This is due to the fact that based on the NCM profiles, the need for DHW is constant. Table 4.6 shows the result of the simulation for a CHP system sized based on the building's need, i.e., 210 kWe and a smaller system, 104 kWe and a larger sized system, 430 kWe. The choice of the alternative CHPs was based on the availability of the systems in the UK market. As always, the equipment energy use is not considered in the value for total energy consumption.

Table 4.6 EPC rating and emission rates for models with CHP system

Model	Heat to power ratio	Size fraction	EPC rating	Energy consumption (kWh/m^2)	CO_2 emission (kg/m^2)
Baseline	-	-	C (51)	310.71	93.42
104 kWe CHP	1.59	0.64	B (43)	344.67	79.73
210 kWe CHP	1.18	0.95	B (34)	370.12	64.2
430 kWe CHP	1.34	2.23	B (33)	379.47	62.22

As illustrated in Table 4.6, all the models with CHP systems have achieved better EPC ratings compared to the baseline model.

As the CHP system size is increased, the reduction in emission is also increased. This is consistent with the literature, where it has been stated that the higher the fraction of the thermal load satisfied by the CHP system, the better the reduction in CO_2 emission (Mago and Smith, 2012).

4.6.5.3 CO_2 emission Vs. energy consumption

Table 4.6 shows that despite the reductions in CO_2 emissions, the energy consumption has increased, so much so that the model with the lowest CO_2 emission rate, i.e., the model with 430 kWe CHP, has the highest level of energy consumption. In order to explain this matter, the mechanism of incorporating a CHP system in EPC calculation is explained in the following paragraphs.

In a CHP system, the efficiency of the process that meets the building's thermal demand (space heating and/or DHW) is affected by the efficiency of the parts and equipment involved. This results in the efficiency of the system to drop. The following scenarios show this statement.

In scenario A – when the CHP system is not yet added - the heat needed for the space heating and DHW of a hotel is provided and transferred through gas-fired boilers and a distribution system with efficiencies of 91% and 90%, respectively. In scenario B, the CHP is added. Now, the efficiency of the CHP system - e.g., 80% - the boilers' and the distribution system's efficiency, and the efficiency of the original mover producing electricity – e.g., a gas engine, a small gas turbine or fuel cell, etc - are all considered in calculating the efficiency of this new system that meets the specified thermal load. Now that the efficiencies of all these elements and equipment are considered, the overall system's efficiency drops.

A reduced efficiency means that meeting the same amount of demand needs more fuel input, resulting in the increase of energy consumption for space heating and/or DHW. Here is when the positive impact of adding a CHP system on the EPC rating emerges. The electricity generated by the CHP, known as grid displaced electricity and its respective CO_2 emission is subtracted from the building's total energy consumption and emission rate. As this generated electricity has a carbon factor of 0.519 kg/kWh, subtracting it usually leaves a considerable impact on the building's final emission, hence a better asset rating and potentially EPC band.

Table 4.7 and 4.8 provide numerical evidence on the previous paragraph's content. In Table 4.7, the energy usage for fixed building services, i.e., space heating, cooling, auxiliary, DHW and lighting for each model are added together. This value is then subtracted by the amount of electricity generated by the CHP, to provide the value for final energy consumption in kWh/m^2.

Table 4.7 Energy consumption and generation in the models

Model	All fixed end-uses energy consumption (kWh/m^2)	Energy generated by CHP (kWh/m^2)	Final energy (kWh/m^2)
Baseline	310.71	0	310.71
104 kWe CHP	414.08	69.39	344.67
210 kWe CHP	508.91	138.79	370.12
430 kWe CHP	531.47	152	379.47

Table 4.8 CO_2 emission and CO_2 displaced in the models

Model	Sum of all fixed end-uses emission (kg/m²)	Emission displaced by CHP (kg/m²)	Final emission (kg/m²)
Baseline	93.42	0	93.42
104 kWe CHP	115.74	36.01	79.73
210 kWe CHP	136.23	72.03	64.2
430 kWe CHP	141.10	78.88	62.22

Table 4.8 shows a similar calculations for CO_2 emission. Emissions from the fixed end-uses in each model are added up. This value is then subtracted by the amount of emission displaced by the CHP. The resultant is the building's emission rate that appears on the EPC certificate in kg/m² per annum.

4.6.5.4 Primary energy consumption

So far, based on the simulation results, it is understood that incorporating a CHP system can improve the hotel's EPC and reduce its emissions, despite the increase in the final energy consumption. The reason behind increase in the energy consumption and the contribution from CHP system to emission reduction was fully explained in the previous section.

The result of these simulations is consistent with the existing literature on the topic of reducing the CO_2 emission (Rotimi *et al.*, 2018; Salem *et al.*, 2018). However, the literature gives credit to CHP system in another aspect and that is reducing primary energy consumption. According to the Directive 2018/844, the definition of primary energy used is "*energy from renewable and non-renewable sources which has not undergone any conversion or transformation process* " (Directive (EU) 2018/844, 2018). In order to provide further explanation, the Building Research Establishment (BRE) puts forward an example: "*The chemical energy contained in fossil fuels is a source of primary energy. However, a unit of electricity generated by burning that fossil fuel would not be considered primary energy because it has gone through a conversion process*" (BRE, 2019a, p. 1). In this aspect also the results of the simulations are consistent with the literature, as regardless of the CHP size, it has contributed considerably to reducing the primary energy consumption, Figure 4.11. The primary energy consumption can be greater than the value shown as final/total energy consumption. The reason is that the primary energy includes the "*delivered energy and allowance for the overheads incurred during the process of extraction, processing and transporting a fuel/energy to the building*" (DCLG, 2013, p. 54). The current primary energy factors for non-domestic buildings are 3.07 and 1.22 for grid supplied/displaced electricity and natural gas, respectively.

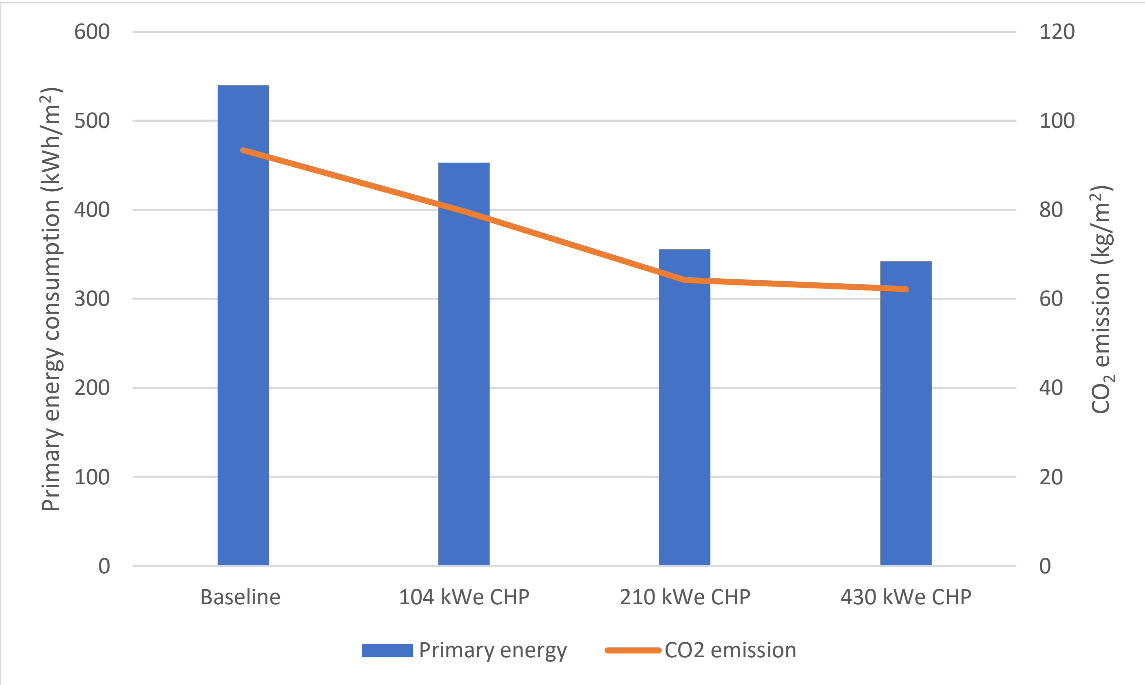


Figure 4.11 Primary energy consumption and CO_2 emission of the models

As shown in Figure 4.11, compared to the baseline model, the primary energy consumption has reduced in all the three models with CHP systems, which is consistent with the literature (Cardona, Piacentino and Cardona, 2006; Mago and Smith, 2012; Fubara, Cecelja and Yang, 2014; Salem *et al.*, 2018).

Furthermore, the graphs in Figure 4.11 suggest that adding an undersized CHP system – i.e., 104 kWe – results in 16% and 14% savings in primary energy consumption and CO_2 emission, respectively. When the properly sized CHP system – 210 kWe – is implemented, the savings in primary energy and CO_2 emission are increased to 34% and 31%, respectively, showing that doubling the size of the CHP system, has doubled the savings compared to the baseline model. But in the third model, despite doubling the CHP size again – 430 kWe – the savings are only marginally better, with 36% and 33% reductions in primary energy and CO_2 emissions. This suggests that an oversized CHP does not necessarily provide more benefits.

4.6.5.5 How does these results sit in reality?

The reason for implementation of a CHP system for this hotel was to investigate the impact on the EPC rating. Based on the simulation results, implementing a CHP system can improve the EPC rating of the hotel. As mentioned earlier, within the existing framework for hotel's EPC calculation, there is a constant need for hot water. As the hot water demand for each activity in a hotel is expressed in $l/d/m^2$, the total demand for hot water in the hotel remains the same on a daily basis. As an example, for this hotel in its baseline model, for every hour of the year there is 259.33 kWh heat consumption for DHW. Therefore, even during July and August – when usually there is no space heating demand – there is a constant need for DHW, resulting in the CHP system proving useful. However, in reality the situation can be different, as the DHW consumption can vary with time and occupancy (Goldner, 1994; Hendron and Burch, 2007; Pang and O'Neill, 2018). Therefore, there might not be a constant need for CHP to run in the actual situation.

This is not to say that in reality this hotel can't benefit from a CHP system, given that the hotel has an active swimming pool, a CHP system can actually be a viable option. This is to say that deciding on whether to implement a CHP system and sizing it should be carried out with contemplations that may not be reflected in the EPC calculation procedure. For that reason, it is very likely that deciding whether or not to implement a CHP system, is not carried out through the EPC assessment. Furthermore, the cost issues will have a significant impact on the hoteliers' decision.

4.7 Summary and conclusion from this chapter

In this chapter, upgrading the EPC rating of an already complying hotel through different measures was investigated. These measures were focused on improving the thermal performance of the glazing elements and using Low/zero carbon technologies such as adding heat pumps and combined heat and power (CHP) system.

In all the three models aiming at improving the glazing elements, the annual energy consumption and CO_2 emission of the hotel were reduced. Based on the simulation results, improving the glazing performance reduced the energy use for heating, cooling and auxiliary end-uses with the auxiliary end-use sustaining the highest reductions in all three models. The maximum reduction in CO_2 emission is acquired when triple glazing units are used. Furthermore, model with Thinsulate film and model with double glazed units performed differently in affecting the cooling and heating energy uses, but their resulting CO_2 emission rates hence the asset ratings are very similar.

The reductions in CO_2 emission rates obviously resulted in better asset ratings for the three models. It also improved the EPC band from C for the baseline model to B. However, it should be acknowledged that this improvement of one EPC band is due to the baseline model's borderline asset rating, i.e., 51.

Based on the simulation results, adding an air source heat pump (ASHP) with an efficiency of 300% for space heating, does not improve the EPC rating significantly, which can be explained through the relatively small share of heating end-use in this hotel. Due to high difference between the carbon factors for grid supplied electricity and natural gas, when the gas-fired boilers were replaced with electric heaters for providing hot water, the EPC rating dropped from band C to D, despite an obvious reduction in annual energy consumption. This simulation signals that every measure that reduces the annual energy consumption, does not necessarily do the same to CO_2 emission.

In the final round of simulations, CHP systems were added. For this purpose, the CHP was sized based on the hotel's base heat load. After sizing the CHP, a smaller and a larger CHP were also selected to investigate the impact of CHP size on the CO_2 emission and EPC rating. All the three CHP models improved the EPC rating and their contribution to CO_2 emission was much higher than the contributions made through glazing improvements and/or heat pumps. Despite the increase in the annual energy consumption – the sum of energy consumption for the five main end-uses – the primary energy consumptions in all the three CHP models were reduced considerably compared to the baseline model. The study found that while having an undersized CHP system provides less benefits in terms of CO_2 saving potentials, having an oversized CHP system on the other hand, provides only marginally better results compared to a properly sized CHP system.

The main conclusions from this chapter can be highlighted below:

- Improving the thermal performance of glazing elements can only provide marginal impact on the EPC rating. This is the case even when the large share of the external façade is covered in glazing.
- The EPC rating is based on CO_2 emission, rather than the energy consumption.
- Regarding the previous point, if a given measure for improving the EPC rating causes a reduction in one end-use and an increase in the other one, depending on the type of fuel used for either of these, the impact on the EPC rating can be different.
- If sized properly, CHP systems can reduce the CO_2 emission so that not only the asset rating is improved, but also an improvement in the EPC band can be obtained.

Chapter 5 Uncertainties surrounding the NCM assumptions for cooling end use in hotels.

5.1 Statement of the situation

As mentioned in the first chapter, the ultimate goal in the hotel industry is to cater for guests' comfort and providing them with good and memorable experiences. Through this, there is higher chances of a revisit from an existing customer while it can also help in receiving good reviews and feedback for the potential new customers.

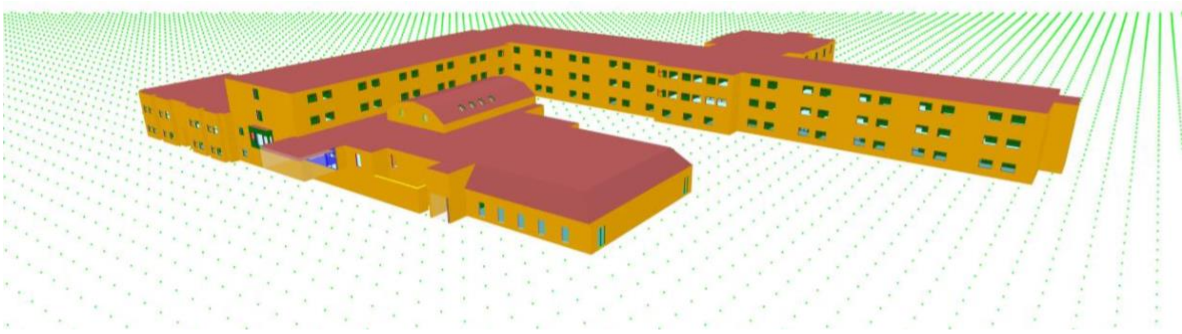
Apart from the cost issues, another challenge for hoteliers when improving their guests' comfort level, is to also meet the energy efficiency requirement. With MEES requirement in action, this is even more crucial.

In this chapter, an issue of this nature is investigated. The hotel under investigation in this chapter is Hilton Watford, a purpose-built hotel from 1970s in Watford, Hertfordshire. In recent years, the hotel officials have received feedback from the guests expressing their dissatisfaction towards lack of cooling systems in the guest rooms. In an attempt to cater for guests' thermal comfort, the hotel's officials considered adding cooling systems to the guest rooms, however, the introduction of MEES requirements and the well-established contribution of comfort cooling systems to electricity consumption, resulted in them pondering over the matter. In this chapter, the potential impact of adding cooling systems on the EPC rating of the hotel is investigated.

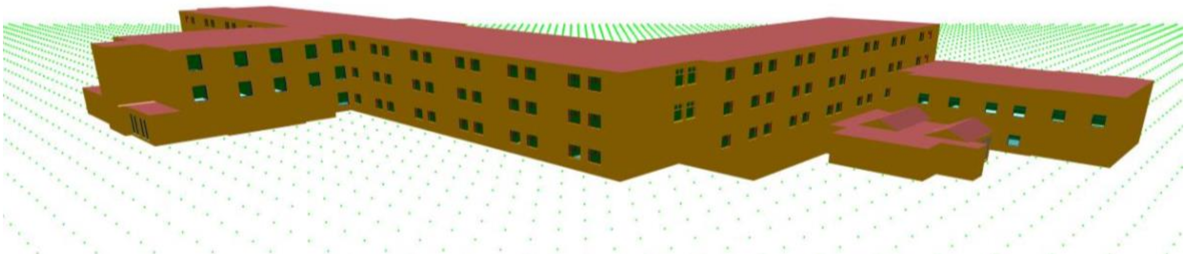
5.2 Building description

5.2.1. Building geometry and fabric

Hilton Watford was built in 1970s. The total floor area of the building is around 10,000 m^2 and it is constructed in four levels, where the lower ground floor level accommodates areas such as the kitchen, restaurant and bar, meeting rooms and a function room. The upper ground floor - the entrance level - accommodates reception and lounge area, conference rooms and some guest rooms. There used to be a swimming pool in this level, which is now converted into a gym. There are in total 202 guest rooms, spread over upper ground floor, first and second floor. The building is not sealed and there is a double-glazed window set in every guest room - 1.5 m wide and 1.15 m long - with two small openable parts on top. The windows in guest rooms are coated with Low-*E* coatings. The benefits of Low-*E* films are discussed in chapter 2. The building's geometry and the floor plans are shown in Figures 5.1 and 5.2.



(a) Front view to the building.



(b) Rear view to the building.

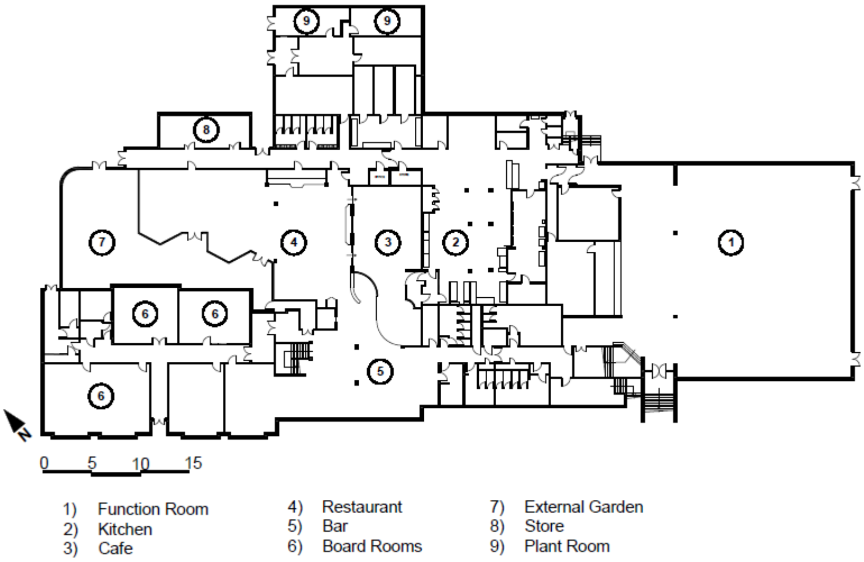
Figure 5.1 Views to the building geometry

5.2.2. Building services

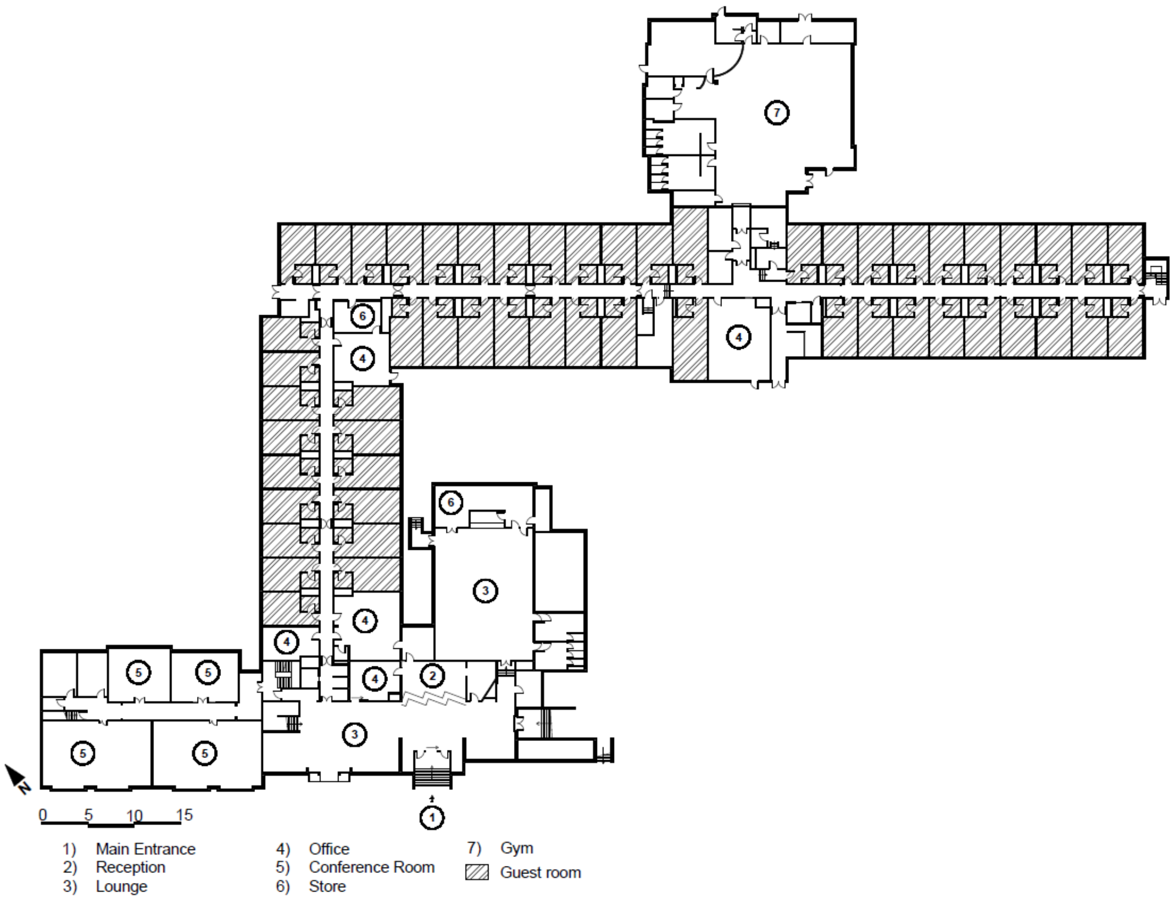
As mentioned, the hotel has 202 ensuite guest rooms. Out of these 202, cooling is provided to only 20 guest rooms. In these 20 guest rooms, cooling and heating is provided through split systems. The other 182 guest rooms do not have access to comfort cooling systems. Heating to these guest rooms is provided through one of the following systems:

- Oil-filled radiators in 107 guest rooms
- Electrical radiators in 18 guest rooms
- Wet central radiators in 57 guest rooms

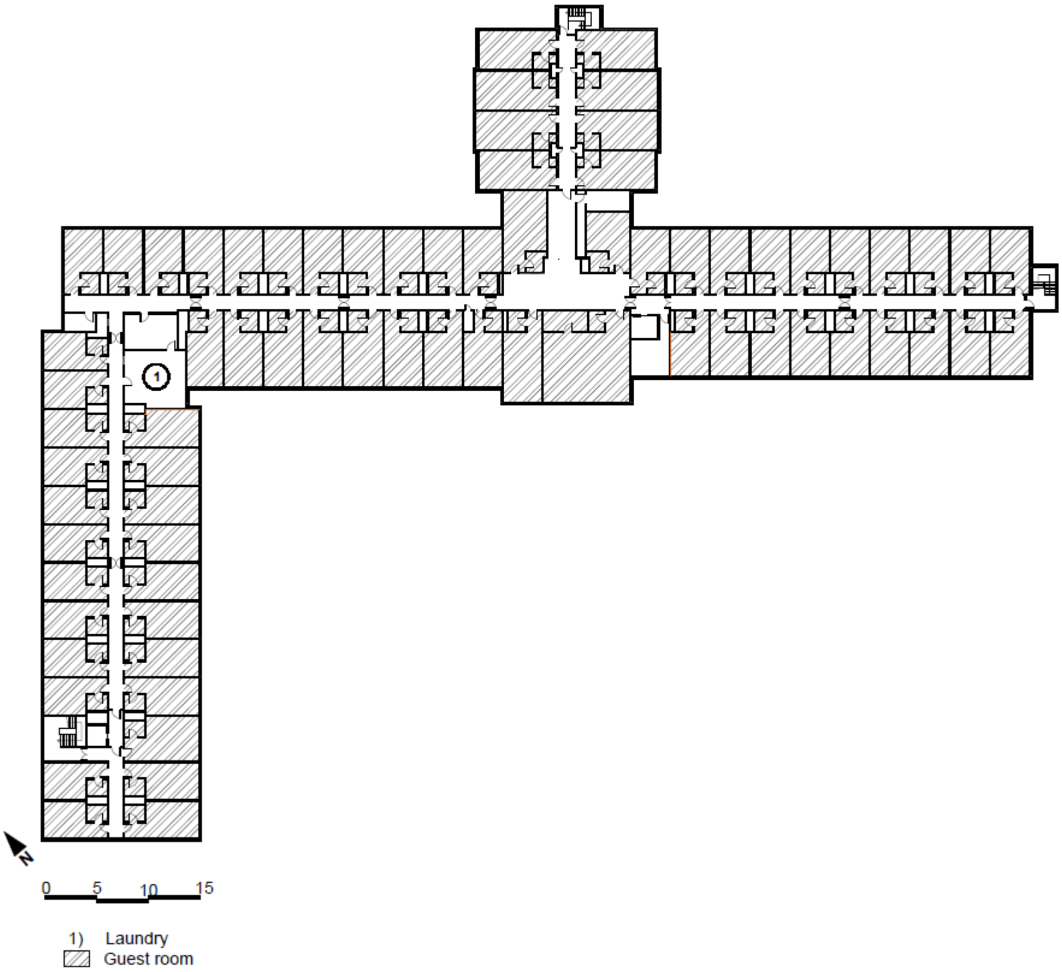
In restaurant and bar areas heating and cooling is provided through an air handling unit and an air-cooled scroll chiller, respectively. Other areas such as the meeting rooms, offices, reception and the gym use split and multi split air conditioning units for both cooling and heating. DHW is provided to different areas of the hotel by gas-fired boilers.



(a) Lower ground floor plan



(b) Upper ground (entry level) floor plan



(c) First and second floors plan

Figure 5.1 Hotel's floor plans

5.3 Modelling assumptions

The weather files used for the simulation is London TRY, as it is the nearest station among the files available. The hotel is located less than 15 miles from Central London. The suitability and usefulness of TRY weather files has been discussed in chapter 3. According to London TRY, the minimum and maximum external temperatures are −3.2°C and 30.7°C, occurring on March 2nd and July 14th, respectively. The graph for hourly outdoor temperature in London TRY weather file is already illustrated in chapter 4, Figure 4.3.

Based on the information collected during the site visit and the common constructions during 1970s - based on NCM's database for construction - the building fabric specifications are shown in Table 5.1. The building was built in 1970s, therefore an air permeability rate of 25 $m^3/(h.m^2)$ @50 Pa was considered for it.

Table 5.1 Building fabric specification considered for the simulation.

Building element	Construction	Calculated area-weighted average U-value (W/m^2K)
External wall	Clear cavity wall (E&W) 1974-1980, consisting of two layers of brick with an air gap of 50 mm	1.45
Ground floor	Solid floor common in pre 1985 construction, consisting of clay underfloor, brick slips, cast concrete and expanded Polystyrene (EPS)	0.84
Roof	Flat roof common in pre-1981 construction consisting of asphalt, plywood deck, asbestos cement, air layer.	1.99
Window (in guest rooms)	Double-layered glazing (4-16-4), Low-*E* coating, air filled	1.54
Window (other areas)	Double-layered glazing (4-6-4), uncoated, air filled	3.28

5.4 Cooling loads

As mentioned, only 20 guest rooms have access to cooling systems (through split units). In recent years, the hotel management has received feedback from the guests about thermal discomfort during summer in guest rooms. In order to attend to guests' comfort, adding cooling systems to all the guest rooms has been brought up as an option. However, its impact on energy consumption and the building's EPC rating has been a matter of concern, especially with regards to the launch of MEES regulation.

In order to estimate the increase in energy consumption and the potential impact on the hotel's EPC rating, the cooling load of these guest rooms should be calculated. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines cooling load as "*the rate of energy removal required to maintain an indoor environment at a desired temperature and humidity condition*" (ASHRAE, 2013, p. 18.1). Usually, the cooling load is calculated through one of the three following methods:

- The simplest method is to use an index and the floor area of the building. The index is determined for typical buildings in typical climatic zones (Lu, 2008; Gang *et al.*, 2015).
- The cooling load for a design day or one-hour is calculated. For using this method, the outdoor weather data and indoor conditions should be known. Weather conditions in this method is considered statistic and the internal gains from occupants, equipment, lighting, etc. are calculated (ASHRAE, 2013; Gang *et al.*, 2015).
- The most sophisticated and comprehensive method of calculating cooling loads is through professional platforms designed for this purpose such as building energy modelling tools. These tools usually use typical meteorological year (TMY) as weather input and occupancy hours and running/working schedules for lighting systems, equipment, etc. (Gang *et al.*, 2015).

The cooling load calculations in TAS is considered from the third method.

5.5 Measured data for the existing hotel

Figure 5.2 shows the measured monthly energy consumption during the period 2012–2018. As shown, the energy consumption of the hotel varies from one year to another. Despite the fluctuations and variations, a pattern of having higher levels of energy consumption during the January–March and October–December can be observed almost for each year, similar to what was observed for the hotel in chapter 4. As the hotel is located in a heating-dominant area, increased energy consumption during the colder months is expected. This is consistent with the literature (Milojković, Nikolić and Stanković, 2012; Cabello Eras *et al.*, 2016). Further discussion on how occupancy rates and outdoor weather temperature affect the monthly energy consumption will be discussed in detail in chapter 6.

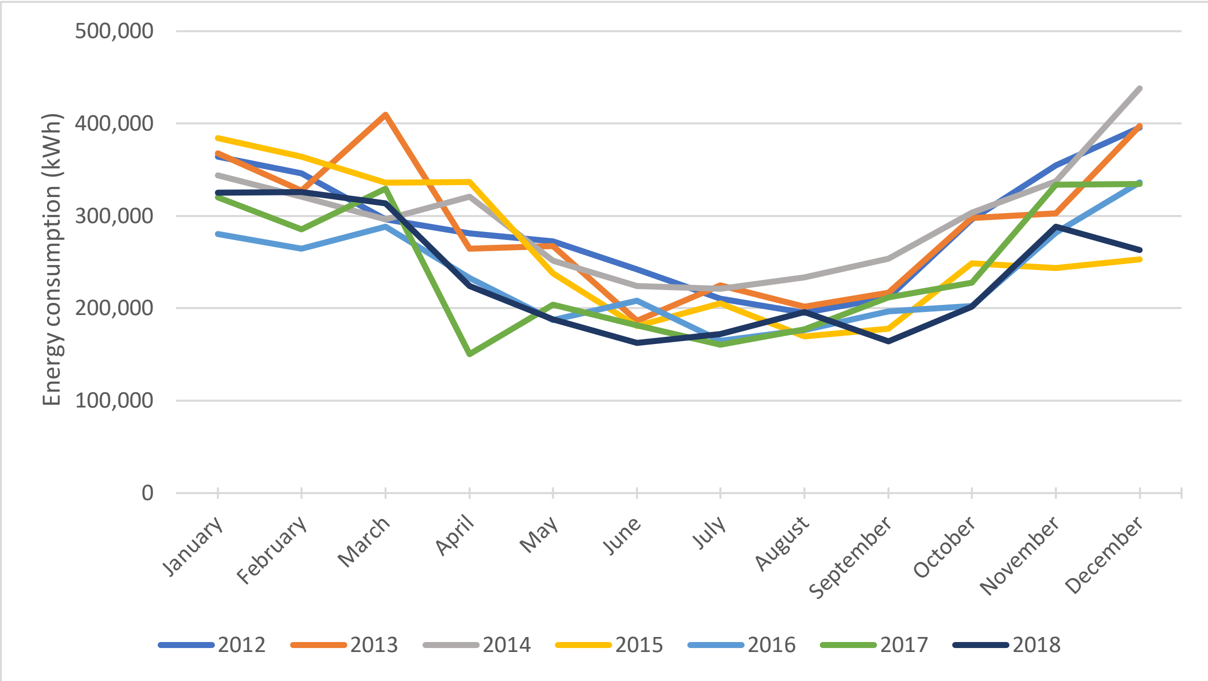


Figure 5.2 Measured energy consumption data for Hilton Watford (2012–2018)

5.6 Simulation results

5.6.1 Baseline model

By carrying out the EPC calculation in TAS, the building in its current condition - which forms the baseline model - receives the EPC band of C with the asset rating of 53. According to the analysis, the annual energy consumption and CO_2 emission of the building are calculated as 314.69 kWh/m² and 100.02 kg/m², respectively.

Figure 5.3 shows the share of each end use in the annual energy consumption of the hotel, estimated by TAS using the building characteristics and NCM standard profiles. As already mentioned in preceding chapters, the end-uses considered in EPC calculations are heating, cooling, auxiliary, lighting and DHW. The simulation also calculates the electricity used for equipment; however, this does not count towards the total for consumption or calculating the emission. The reason behind this is that the minimum calculations required by the EPBD is not inclusive of the equipment end-use.

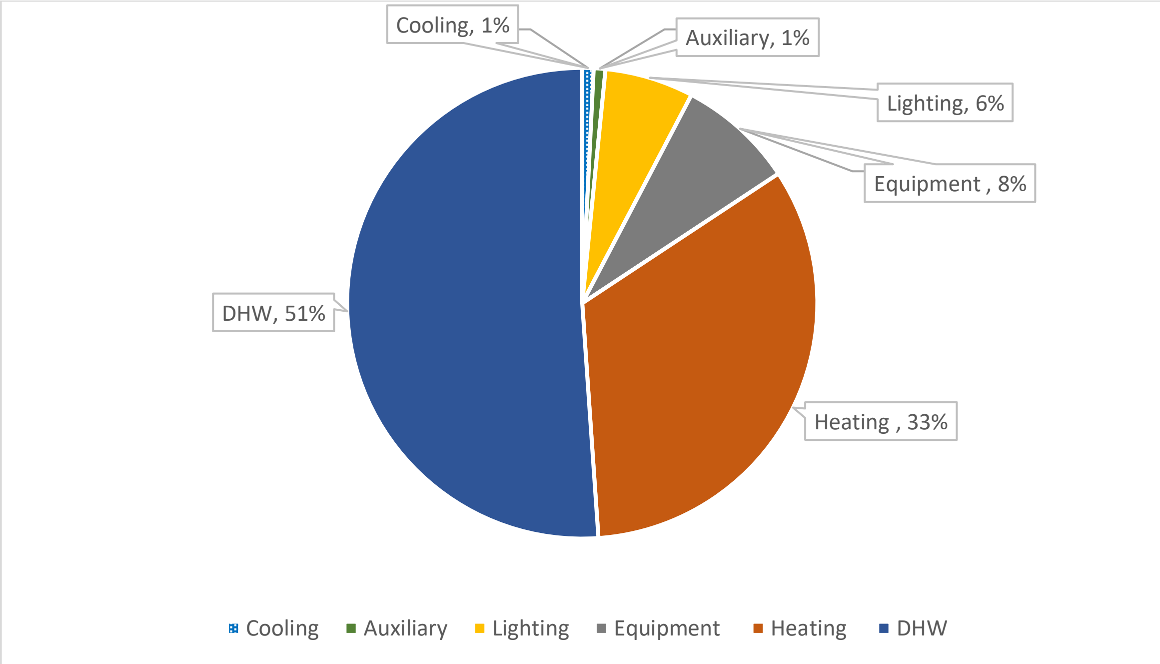


Figure 5.3 Share of end uses in annual estimated energy consumption.

Based on the software's estimation, The DHW and heating are the two most energy intensive end-uses in this building and their joint share adds up to more than 80% of total energy consumption. The share of 33% for heating is due to hotel's heating dominant climate, relatively high level of U-values in building elements (compared to the limiting values in existing Building Regulations) and the high air permeability rate. The share of DHW is calculated to be 51%. As it will be discussed further in chapter 6, this may not be a real reflection of actual situation in the hotel

Another point to be noted from Figure 5.3 is the almost negligible share of cooling energy use, despite many areas within the hotel such as the restaurant, halls, offices and conference rooms having access to the cooling systems. It is difficult to find information about this energy-use from other studies, as the existing literature mainly expresses the share of air conditioning. Air conditioning is beyond just adjusting the temperature. It includes supplying regular fresh air, decontaminating it and adding/removing humidity, and finally adjusting the temperature. For instance, for both US (WTO, 2011) and Greece (Karagiorgas, Tsoutsos and Moiá-Pol, 2007) the share of air condition is 15%, however, the share of energy expenditure on cooling end-use is not clear.

Also, with majority of zones having local systems i.e., split/multi split units or electric radiators rather than being linked to a central system and in the absence of mechanical ventilation, the very small share of the auxiliary end use is justifiable

5.6.2 Comparing the simulated data with the measured data

As it is a common practice in energy simulation studies, the energy consumption predicted by the software is compared with the measured data, Figure 5.4. Although monthly measured data is available from previous years, but for the purpose of comparison, it is best to focus on the recent years as they are closest to the current situation in terms of any changes to the building and its services.

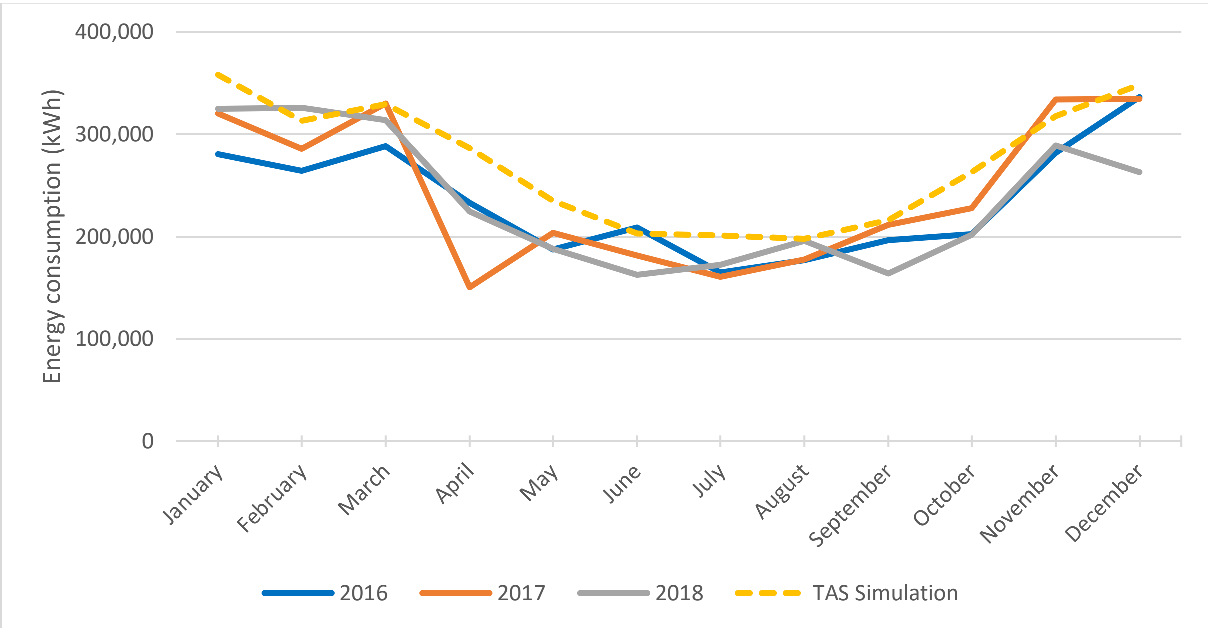


Figure 5.4 Comparing the simulation results with measured data

From the graph in Figure 5.4 it is understood that the simulated data is an overestimation of the monthly energy consumption. While every effort has been taken to ensure that the modelling replicates the actual building in every aspects, the role of occupant behaviour and default values in increasing the gap between simulated and measured data should not be overlooked. Given the nature of EPC calculations - compliance modelling - and the normalised weather data used in this study, the gap between estimated and measured data is prone to increase.

The two statistical indicators introduced in chapter 3 are used to compare the simulated and the measured energy consumption data, Table 5.2. Again, given the positive values for MBE, it can be concluded that the EPC analysis for this hotel is an overestimation of its actual/measured energy consumption.

Table 5.2 Statistical indicators for estimated data when compared with measured data of three years

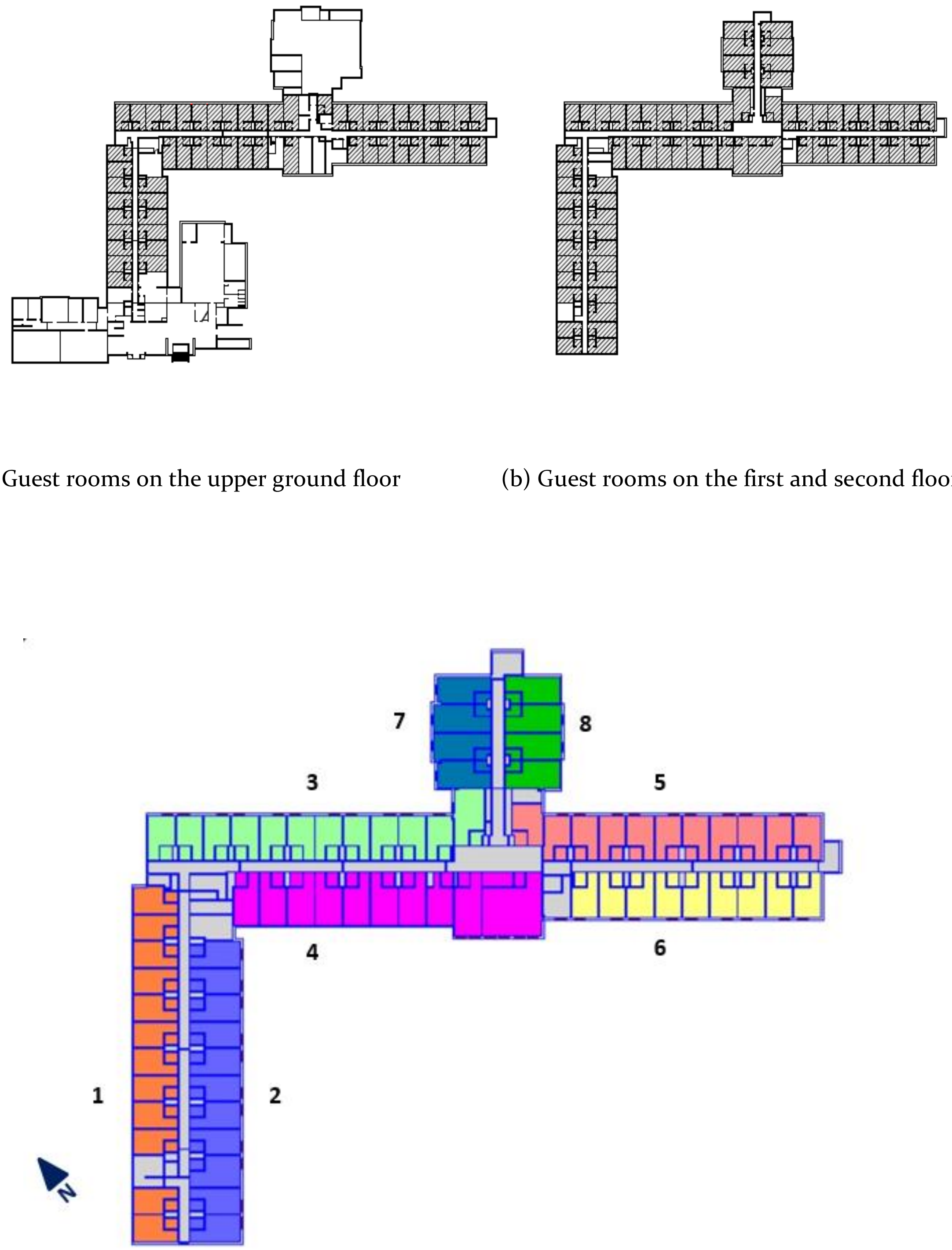
	2016	**2017**	**2018**
MBE	15.87%	12.02%	15.68%
Cv (RMSE)	18.39%	19.08%	19.20%

5.6.3 Model with cooling systems for guest rooms

By considering the heat gains from all sources, guest rooms' cooling loads are calculated. Some of heat gains are directly determined by the NCM assumptions. For example, the lighting gain, the occupancy latent and sensible gains and the equipment latent and sensible gains are all designated by the NCM standard profiles for the guest rooms. These gains are the same for all the guest rooms in the hotel.

However, heat gains from other sources can be different form one guest room to another. For example, heat gains from solar radiation depends on the guest room's location and orientation. Furthermore, depending on whether the adjacent zone is heated or not, the heat transfer mechanism can be different for each guest rooms. Figure 5.5 groups the guest rooms according to their planar orientation and vertical location, followed by Table 5.3 where the cooling loads for each group of guest rooms are depicted. The loads are calculated based on NCM standard profiles for hotel guest rooms. Based on these standard profile, the cooling set point (CSP) for hotels' guest rooms is assumed at 25°C.

As shown in Table 5.3, the guest rooms on the second floor i.e., the top floor, have the highest levels of cooling loads. This is due to the fact that guest rooms on the second floor have their top surface (i.e., the roof) exposed to the Sun, resulting in receiving significantly higher amount of solar gain, Figure 5.6, while the rooms on the upper ground floor have the least amount of cooling loads due to being in the shaded area of the rest of the building.



(a) Guest rooms on the upper ground floor (b) Guest rooms on the first and second floor

(c) Dividing the guest rooms according to their planar orientation.

Figure 5.5 Illustration of guest rooms on different levels and orientations.

Table 5.3 Cooling loads for guest rooms with the cooling set point of 25°C

	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	Zone 7	Zone 8	Total per level
UGF[1]	61.69	75.98	0	0.62	0	1.36	-	-	139.65
FF[2]	191.50	285.88	80.08	193.84	75.42	104.74	71.37	74.60	1,077.43
SF[3]	319.56	410.90	290.51	439.20	253.26	269.35	160.79	176.93	2,320.50
Total per zone	572.75	772.76	370.59	633.66	328.68	375.45	232.16	251.53	3,537.58

1 UGF: Upper Ground Floor
2 FF: First Floor
3 SF: Second Floor.

Having a cooling load of 0 – e.g., zones 3 and 5 – shows that based on the heat transfer mechanisms happening in those zones, the indoor dry bulb temperature never exceeds the set value of 25°C in those guest rooms, therefore no amount of heat needs to be removed from those zones to keep their indoor temperature at the specific value of 25°C.

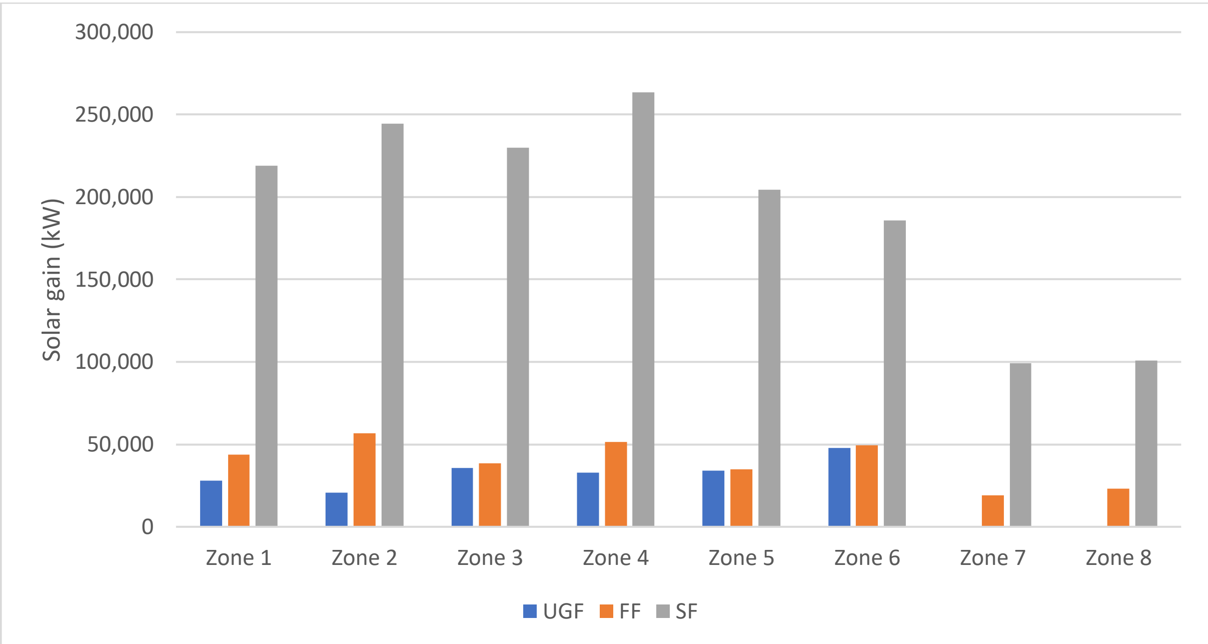


Figure 5.6 Solar gain (kW) on external surfaces for different groups of guest rooms

The total cooling load for all 202 guest rooms, with CSP of 25°C, is 3,538 kW which means in order to cool down the guest rooms to 25°C (from any higher temperature), 3,538 kW of heat should be removed from guest rooms. As mentioned earlier, split units are already in place in 20 guest rooms - zone five on the first floor and zone six on the second floor. Therefore, the cooling load for the remaining guest rooms is around 3,193 kW.

Due to existing situation in the hotel, it is assumed that the cooling systems will be provided locally, for example through split/multi split units. Depending on the system's energy efficiency ratio (EER), the amount of electricity needed for meeting the 3,193 kW of cooling load will be different. Using the minimum recommended value set by the non-domestic building services compliance guide (HM Government, 2013) i.e. 2.6 for cooling systems' EER, the amount of electricity consumed to provide cooling to the 182 guest rooms would be almost 580 kWh, emitting an extra 301 kg of CO_2.

With the new cooling systems added, the temperature in these guest rooms will not exceed the 25 °C, resulting in potential changes in heat transfers between these guest rooms and their adjoining zones. As the cooling system result in having different surface and air temperature in the guest rooms, their heat transfers to their adjoining zones through conduction and air movement will undergo some change, resulting in new heat balances for each surface/zone in the hotel. After accounting for all these changes in heat transfer mechanisms, the hotel's asset rating undergoes an almost negligible change. The new EPC of the hotel is C (54). This denotes that adding cooling systems with an EER of at least 2.6 would not adversely affect the EPC rating of the hotel, or its compliance with MEES requirements.

On the other hand, if the systems considered for providing cooling to these guest rooms, are chosen to provide the rooms with heating as well - as it is a common practice in this business - the heating energy consumption would be reduced significantly. This reduction in heating energy consumption is caused by these systems' higher heating efficiency compared to that of the current heating systems in the guest rooms. While the efficiency of current systems - wet central radiators, oil-filled radiators, electrical heaters - are all considered to be 0.91 (91%), the minimum coefficient of performance (CoP) for split systems would be 2.5. Comparing the values in fifth and sixth rows of Table 5.4 illustrates the reduction in CO_2 emission when the existing heating systems in the guest rooms are replaced.

Table 5.4 Heating energy consumption in the guest rooms in baseline model and when current heating systems are replaced by the split units

Heating System	Heating Efficiency	Heating Energy (kWh)	CO_2 factor (kg/kWh)	System's CO_2 emissions (kg)
Electrical radiators	0.91	96,139.13	0.519	49,896.21
Oil-filled radiators	0.91	413,570.23	0.519	214,642.95
Wet-central radiators	0.91	325,689.75	0.216	70,348.99
Total (current situation)	-	835,399.11	-	334,888.14
Split systems in all guest rooms	3	264,752.91	0.519	137,406.76

As shown in Table 5.4, the heating energy consumed by electrical radiators, oil-filled, and wet-central radiators – all with efficiency of 91% - are approximately 96,000 kWh, 413,000 kWh and 326,000 kWh, respectively. Given each system's fuel type and its corresponding CO_2 factor - in fourth column - the CO_2 emission from electrical radiators is almost 50,000 kg, and the numbers for oil-filled radiators and wetocentral radiators are around 214,000 kg and 70,000 kg, respectively. The total CO_2 emission from these three systems sums up to around 335,000 kg, as illustrated in fifth row of Table 5.4. Now, if all these three heating systems i.e., electrical heaters, oil-filled and wet-central radiators are removed and replaced by split units with a CoP of 3, the total energy consumption for heating end-use would be reduced to slightly less than 265,000 kWh and the amount of CO_2 emission would be reduced to less than 138,000 kg. As shown in the last row of Table 5.4, a reduction of almost 59% in heating-induced CO_2 emission of the hotel is achieved when the existing heating systems in guest rooms are replace by split units.

The significant reduction in CO_2 emission from heating is larger than the increase caused by the extra cooling consumption. Therefore, the total annual emission rate of the hotel – which was 100.02 kg/m^2 in the baseline model – would drop to 79.2 kg/m^2. The EPC band is improved to band B with the asset rating reaching a value of 42.

5.6.4 A more realistic look into the matter

All the simulations reported in this chapter so far, has the guest rooms CSP at 25°C, as per requirement of NCM guidelines. While from the policy point of view and for the purpose of comparability of EPCs, choosing a default value may look justifiable, it is worth taking a deeper look in more realistic options, for example if the guests opt for lower temperature in their rooms, especially as it is claimed that saving energy is not always among the hotel occupants top concerns (Moon *et al.*, 2015) and less energy-conscious behaviour can often be expected from people when they are staying at a hotel (Santamouris *et al.*, 1996; Roberts, 2008; Rotimi *et al.*, 2017). In order to further investigate the potential increase in the energy consumptions and CO_2 emission if the guests choose to have a cooler indoor environment in their room, extra rounds of simulation were carried out with lower CSPs for guest rooms. The choice of the temperature range was based on the CIBSE recommendations for summer temperature in hotel guest rooms (CIBSE, 2015). The range recommended is 21°C–25°C. In these new round of simulation, the EER for the cooling system was considered to be 3, as it was intended to investigate the more realistic situations beyond compliance. Currently in the UK, split units with much higher EER are commercially available.

Table 5.5 shows the cooling load and energy consumption for CSPs below the NCM's standard value of 25°C. Those 20 guest rooms with cooling systems already in place are also included in the values in this Table.

Table 5.5 Cooling loads and energy consumption for a range of cooling set points

	25 (default)	**24**	**23**	**22**	**21.5**
Cooling load (kW)	3,537.57	9,135.92	20,515.04	39,207.58	51,758.90
Cooling energy consumption (kWh)	649.87	1,385.26	3,351.44	7,348.73	10,476.73
Increase in guest rooms cooling-induced CO_2 emission compared to the default CSP (kg)	0	381.67	1,402.12	3,476.71	4,718.47

Increase in guest rooms cooling-induced CO_2 emission compared to baseline model (kg)	303.83	685.51	1,705.95	3,780.55	5,100.14

In order to calculate the increase in guest rooms CO_2 emission when lower CSPs are used, the following procedure is taken:

By using the numbers in the third row of Table 5.5, the difference between the cooling energy consumption in every model with a new CSP and the model with default CSP (25°C) is calculated. Example for CSP 24°C is shown below:

1,385.26 - 649.87 = 735.39 kWh ⟶ increase in the guest rooms cooling energy use when the CSP is reduced from 25°C to 24°C.

This difference is then converted into CO_2 emission by using the grid electricity carbon factor, i.e., 0.519 kg/kWh:

735.39 × 0.519 = 381.67 kg CO_2 ⟶ increase in the CO_2 emission

The procedure for calculating the increase in CO_2 emission compared to the baseline model is similar. The only difference is that the calculations are based on the cooling energy in the baseline model.

As mentioned, the recommended range by CIBSE is 25°C–21°C, while in Table 5.6, the CSP in the last column is set to 21.5°C. The reason behind this is to avoid on overestimation of energy consumption which is explained in the following lines:

With the guest rooms having a heating set point of 21°C - another standard assumptions by NCM - choosing the same value for the CSP would have resulted in an unrealistically huge amount of energy consumption. This is because it would have meant that at every given hour, if the room temperature was below 21°C, the heating systems would operate to heat the room and then immediately after reaching 21°C, the cooling would be started. To avoid this, the CSP for May to September – i.e., the time period when the building is likely to have cooling loads – was set to 21.5°C, while for the rest of the year it was set to 22°C.

As Table 5.5 shows, lower CSPs result in higher cooling loads for the guest rooms, and essentially higher levels of energy consumption would be needed for meeting those loads. This can also be explained through correlation and regression analyses. There is a very strong correlation between CSPs, and the cooling load as shown in Figure 5.7. The scatter plot in Figure 5.7 shows that not only the cooling loads and CSPs are inversely correlated but also up to 94% of changes in the cooling loads can be explained by the changes in CSPs.

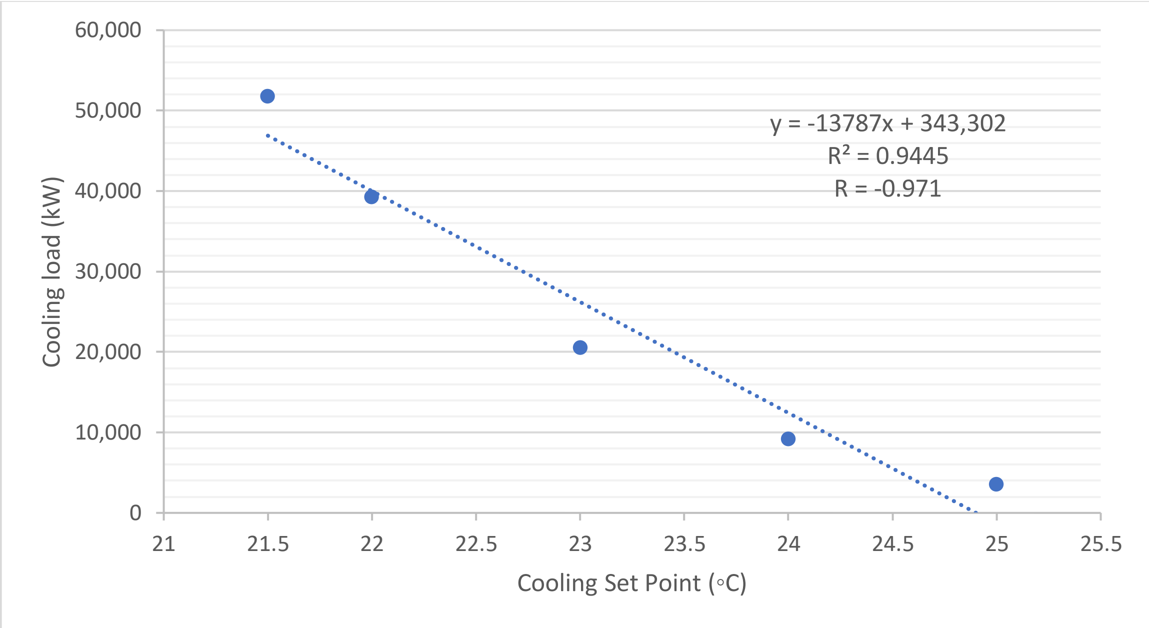


Figure 5.7. Scatter plot showing the relationship between CSP and cooling loads

5.7 Discussion

As discussed, in order to generate the EPC, the standard internal conditions of the NCM should be followed, including the default cooling set point of 25°C for hotel guest rooms. As demonstrated, with the default values, the resulting energy consumption and CO_2 emissions are not large enough to change the EPC band. As far as the compliance modelling and EPC generation is concerned, the extra 182 split units do not cause a remarkable change on the building's energy performance. However, in real situation, there is no guarantee on what temperature the occupants decide to have in their rooms. Chances are when the cooling systems is provided in a guest room, the occupants would not wait for the room temperature to exceed 25°C and they start using the facility way before reaching that temperature. The potential increase in energy consumption and CO_2 emissions were illustrated in Table 5.5.

Although it was also demonstrated that using the new split units for heating can improve the overall performance of the building due to a significant increase in heating efficiency, the main point is that in the current approved procedure adopted in the UK for hotels' EPC generating, the impact of cooling systems is underestimated. This can also be important for the hotel's management team, that while the impact may not be recognised by the current compliance procedure and EPC assumptions, but beyond the theoretical values, the new cooling systems can increase the electricity consumption hence the costs considerably.

The cooling set points assigned by NCM Activity database are based on zones' dry bulb temperatures which are highly affected by the external temperature provided by the weather files. As mentioned, TRY weather files are used for EPC calculations. A TRY weather file is composed of 12 separate months of data each selected to represent the most average month from the data collected (CIBSE, 2017b). Therefore, the TRY weather files are a "normalised" nature. With the expected rise in temperature, Future weather files for three time periods i.e., 2020s (2011-2040), 2050s (2041-2070) and 2080s (2071-2100) and different emission scenarios are released by CIBSE, which might be a better choice for calculating the cooling loads in the contexts of the expected rise in temperature. However, until now, only the current TRY weather files are approved for compliance modelling in the UK. Updating the recommendations on using the future weather files - when appropriate - can help in improving the quality of simulations of such.

The focus of this chapter was on guest rooms, as it was the real-case scenario happening in the hotel. The NCM's CSPs for other zones within a hotel are between the range of 21°C–25°C, some of them highlighted in Table 5.6. How realistic these zones CSPs are, has not been investigated in this chapter, however, given the fact that the area covered by these zones are considerably less than that of guest rooms, the impact from using lower CSPs in some of these zones (e.g., restaurant and gym areas) is considerably less than that of the guest rooms.

Table 5.6 CSP for zones other than guest rooms in a hotel assigned by the NCM Activity database

Zone	CSP (°C)	Zone	CSP (°C)
Changing area	25	Circulation	23
Eating/drinking area	25	Hall	23
Fitness/gym	25	Reception	23
Office	24	Food prep/ kitchen	21

The points discussed above suggest that unrealistic assumptions about cooling set point in guest rooms can lead to an underestimation of cooling energy consumption hence underestimation of CO_2 emissions from this end-use. The impact from this underestimation can be further discussed:

- One application of EPC analysis is to suggest where the energy efficiency retrofitting measures should be focused in order to improve the energy efficiency of the building. When cooling energy consumption is underestimated, its share in annual energy consumption breakdown is less than what it should be. A lower share in annual energy consumption breakdown signals that improving the energy efficiency of that end-use (cooling here) will not result in considerable savings in overall energy consumption and electricity costs. This can be a deviation from reality where the share of cooling energy consumption can be much higher.
- Studies and forecasts suggest that with the expected rise in temperature (Pieri, IoannisTzouvadakis and Santamouris, 2015), cooling demand is increased by three times between the period 2010 to 2050 (Souayfane, Fardoun and Biwole, 2016). In the EU, it is likely that the year 2030 sees an increase of 70% in the space cooling demand compared to the level in 2010 (Kemna and Moreno Acedo, 2014). So, it is safe to assume that the UK will experience a surge in installation and using cooling systems in different sectors, of which, hotels are no exception. As aforementioned underestimation is caused by the NCM guidelines, it affects all the hotels in the UK applying for an EPC. With the expected increase in the usage of cooling systems, the implications of such uncertainty can be extended even further.

With the points discussed above about the impact of adding cooling systems on increasing the CO_2 emissions - even in the absence of an adverse effect on EPC - it is worth considering other measures for improving guests' thermal comfort. One of these means is natural ventilation. Currently, the windows to the guest rooms have a relatively small openable area, less than 30% of the total glazing area in each guest room. By increasing the openable part of the windows, the occupants may be able to experience higher levels of thermal comfort.

Although the natural ventilation may not always be enough to fulfil the occupants' thermal comfort levels, some studies suggest that hotels' guests tend to have a higher tolerance of and flexibility towards their environment for sustainability and energy conservation reasons (Han *et al.*, 2011; Buso, Becchio and Corgnati, 2017). However, the cost of changing the windows for all the guest rooms might be an issue.

5.8 Summary and conclusion

In this chapter, the impact of adding cooling systems to 182 guest rooms on the annual energy consumption, CO_2 emissions and EPC rating of Hilton Watford was studied. As required, the EPC calculation was carried based on the NCM standard profiles for hotel buildings, according to which the cooling set point of 25°C was considered for the guest rooms. The weather file used for the study was London TRY. The resulting increase in the energy consumption and CO_2 emissions was small, and therefore the hotel's EPC remained in band C with a marginal impact on the asset rating, going from C (53) in baseline model to C (54) in the model with cooling systems. Furthermore, if the new systems are also used for heating these guest rooms, due to an increase in heating efficiency – compared to the existing systems – the EPC rating will even improve. To check the impact of occupants' behaviour in choosing to have lower temperatures in the guest rooms and based on the CIBSE's summer temperature for hotel guest rooms, further simulations were conducted using CSPs from the range 21.5°C–24°C. As expected, with lower CSPs, the cooling loads, cooling energy consumption and CO_2 emissions are increased considerably. However, these assumptions are not considered in the process of EPC generating.

Based on the results of the simulations and what has been discussed in this chapter especially in terms of the expected rise in using cooling systems in commercial buildings in the UK, the current EPC generating process does not reflect the real consequences of adding cooling systems to guest rooms. In order to achieve the goal behind launching the MEES requirements - which is to effectively reduce CO_2 emissions - steps need to be taken towards improving the current procedure in EPC generating and making them more realistic.

Chapter 6 Uncertainties in the procedure of EPC generating in the UK

6.1 Statement of the situation

With the EPC scheme having been first introduced in EPBD 2002, and its importance further emphasised in the EPBD Recast in 2010, it is now almost a decade since many countries have started using the scheme to evaluate the state of energy performance in their respective countries' building sector. Despite its recognised impact on energy policies around the EU and its contribution to incentivising property owners to improve the energy performance of their buildings, researchers have called for more in-depth look into the reliability and quality of the EPC schemes. Concerns over the scheme's quality and reliability have been stronger in regions where theoretical data and default assumptions rather than measured data are used in EPC assessments. Examples of such studies from different EU countries were presented and discussed in detail in chapter 2. While the majority of those studies are focused on domestic EPCs, the need for investigating the reliability and quality of non-domestic EPCs is evident.

The study in chapter 5 showed that the current procedure for generation of EPCs comes with assumptions that may not be reflective of the energy performance of a building, especially with regards to the standard internal profiles from NCM. In line with the findings from chapter 5, this chapter aims to look at some other aspects of non-domestic EPCs, specifically what can help improve the reliability of the scheme in future revisions.

In this chapter, first the EPCs for three hotels - Hilton Reading, Hilton Watford and DoubleTree Docklands - generated by two accredited software packages are compared. These software tools are EDSL TAS - used throughout this thesis for running simulations - and SBEM. As mentioned in chapter 1, SBEM is the UK Government's Simplified Building Energy Model widely used by commercial assessors for non-domestic EPCs (Communities and Local Government, 2018) and TAS is one of the three Dynamic Simulation Models approved by the Government for the same purpose. As clarified in previous chapters, both of these tools apply NCM standard profiles for calculating EPCs. A summary of the input data used by either of these two and the corresponding source for extracting the data is provided in Table 6.1.

Table 6.1 Summary of input data needed for EPC generating and its source in either of the two software

Input data	Source for SBEM	Source for TAS
Building geometry	Assessor reads from drawings or direct measurements.	Assessor models the building in 3D Modeller module of the software based on direct measurements or from drawings
Weather data	Internal database	Internal database in the Building Simulator module or CIBSE TRY/DSY weather files
Activities assigned to each zone	Selecting from internal database based on the site visit or according to the documents	Zones are introduced by the assessor based on the site visit or according to the documents
Occupancy profiles for activity areas	For consistency purposes, assessor selects the NCM standard profiles for the building type and activity	For consistency purposes, assessor selects the NCM standard profiles for the building type and activity
Building fabric specification/ construction	Assessor selects from an internal Construction and Glazing database or define their user-defined construction	Assessor selects from NCM Construction database or define their user-defined construction
HVAC systems	Assessor selects from internal database or inputs data directly	Assessor selects from internal database in UK Building Regulation 2013 Studio
Lighting	Assessor selects from internal database or inputs data directly	Assessor selects from internal database or inputs data directly

Prior to carrying out the EPC assessment in TAS for each of these hotels, an EPC calculation had been done through SBEM by independent commercial assessors. For all the three cases, the TAS-generated EPC showed smaller asset ratings compared to those from SBEM assessment. This difference in asset rating, has resulted in different EPC bands, Table 6.2.

In light of differences and in the absence of measures for ensuring the reliability of EPC calculations (see chapter 3, section 3.3.5), TAS models were checked repeatedly to ensure they closely represented their corresponding real case situations, and the simulation results were compared with the measured data. After that, the reason behind these discrepancies is looked for in the two software's assumptions.

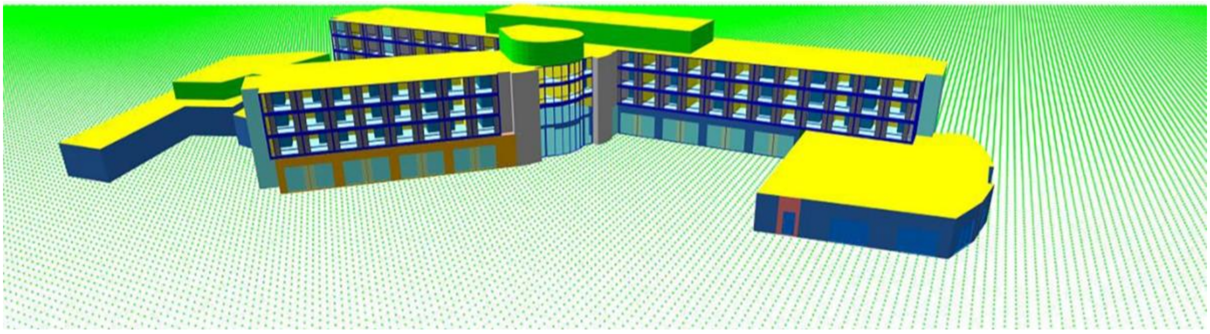
Table 6.2 EPC bands and asset ratings for the hotels by the two software

Hotel	EPC by SBEM (by independent assessors)	EPC by TAS (by the author)
Hilton Reading	C (57)	B (50)
DT Docklands	E (111)	C (74)
Hilton Watford	C (59)	B (48)

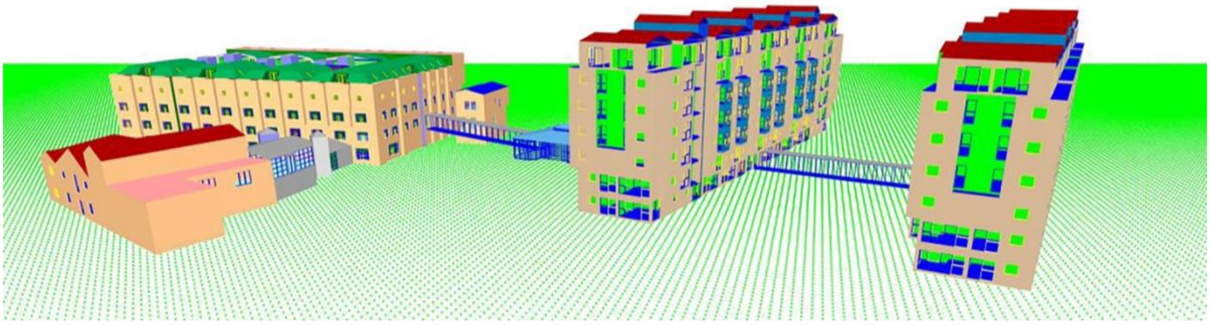
Upon finding the contributing factor, new rounds of simulations for all the three buildings are carried out in TAS with the modified factor and the results are again compared with SBEM scores and the procedure of comparing with measured data is carried out once more. The outcome of this second round of simulation encouraged a deeper look into the current EPC generating procedure resulting in the discovery of a potential source of overestimation.

6.2 Building description

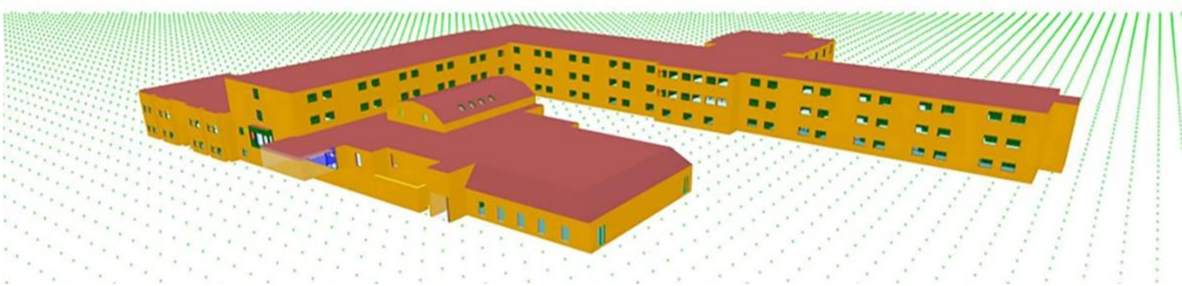
Hilton Reading and Hilton Watford have already been introduced in chapters 4 and 5, respectively. The third case, DoubleTree Dockland is a hotel complex comprising of several different buildings, covering a total area of around 18,000 m^2. Two buildings within this complex are from 19th century, with solid brick and stone construction. One of these two older buildings accommodates guest rooms, restaurant and bar and gym while the other one is purely for conference rooms, offices, and halls. The rest of the buildings in the complex, i.e., two residential towers and the reception building were built in 1980s. The towers have cavity wall construction, and the reception building is covered in glazing. The buildings are connected with foot bridges covered with single-layered glazing. None of the buildings within this complex are sealed and the windows are double-glazed, air filled units with no coating. In terms of services, there is a variety of systems involved. In the old building, the heating and cooling is provided through air handling units and chillers. The demand for DHW is met through electric heaters in this building. The other old building, accommodating conference rooms and meeting rooms, is mainly serviced by split units. The reception building is heated and cooled through split and multi split units. The two towers both have gas-fired boilers for DHW. One of the towers uses the boilers also for heating and the cooling is provided through chillers. The other tower receives heating and cooling through variable refrigerant flow (VRF) systems. Both towers have suites on their top floor (sixth floor) with split units providing heating and cooling for them. Finally, the foot bridges are equipped with individual wall-mounted electric heaters. Figure 6.1 and Table 6.3 provide a summary of the information for these three hotels.



(a) Hilton Reading



(b) DoubleTree Docklands



(C) Hilton Watford

Figure 6.1 Geometries of the hotel buildings

Table 6.3 Information about the cases studied in this chapter

Hotels	Location/ Year of construction	Floor area (m^2)	Heating system/ Cooling systems	DHW
Hilton Reading	Reading 2009	~12,300	Fan coil units served by air handling units and chillers	Gas fired boilers
DT Docklands	London 1800s and 1980s	~18,000	- Fan coil units served by air handling units and chillers - VRF systems - Splits and multi splits units	Electrical heaters and gas fired boilers
Hilton Watford	Watford 1970s	~10,000	- Electrical, and central radiators/ natural ventilation for most of the guest rooms - Split and multi splits for public area and a few of guest rooms	Gas fired boilers

6.3 Results

6.3.1 Initial results

As briefly mentioned, the EPC results by TAS for the three hotels were different to those acquired through SBEM (see Table 6.2). Despite the evidence that the different EPC assessors tend to evaluate the same building differently even when they use the same tool (Jenkins, Simpson and Peacock, 2017) and in the absence of approved measures for validating the EPC results, greatest possible effort was made to ensure that TAS models were exact replications of the actual buildings and that the internal conditions reflect the actual conditions with respect to NCM profiles. The simulations were compared with measured data using the statistical indicators introduced in chapter 3, Table 6.4.

Table 6.4 Statistical indicators for TAS simulation results when compared with measured data (before finding the factor contributing to the discrepant results)

	Hilton Reading	DT Docklands	Hilton Watford
MBE	-8.2%	13.9%	3.8%
CV(RMSE)	15.9%	15.9%	15.8%

As discussed previously, the acceptable tolerance prescribed for these indicators are within the context of operational simulations and/or performance modelling (US Department of Energy, 2015) and no guideline has been identified for the acceptable range within compliance modelling. Given that in a compliance modelling e.g., EPC calculation, certain default values should be used, examples of which include but are not limited to specific occupancy hours, density of occupants in different zones, heating and cooling set points and DHW demands (DCLG, 2013, 2015) (see chapter 2, section 2.2.2 and chapter 3, section 3.2 for more details), and given the normalised nature of the CIBSE TRY weather files, the tight tolerance ranges suggested by US Department of Energy (2015) for the performance modelling would be very hard to achieve, if at all possible.

With that said, the values in Table 6.4 suggest that EPC calculation by TAS is overestimating the actual energy consumption for Hilton Watford and DT Docklands. This is especially noteworthy as between the two software's calculations, TAS is the one with lesser energy consumption and CO_2 emission rates hence better ratings, and yet it is an overestimation of the actual energy consumption for two out of three cases.

Overestimation of energy consumption by EPC calculation for buildings rated as inefficient has also been detected by Majcen, Itard and Visscher (2013) and Gram-Hanssen and colleagues (2017). The higher level of overestimation in the DT Dockland model is partly due to the nature of the hotel's construction and the assumptions made in the relevant standards. As mentioned, two out of four main buildings in the hotel complex are built in mid-19th century with solid brick and stone walls - common in pre 1919 constructions. There is evidence from literature that the U-values of solid walls are significantly lower than the standard values considered in guidelines and standard assessments (F. G. N. Li *et al.*, 2015; Lucchi, 2017) resulting in an overestimation of the energy consumption. Furthermore, Lauren *et al.* (2013) believes that the risk of overestimation of energy consumption in EPC calculations increases with the age of the building.

6.3.2 Finding the main contributor to the discrepancy

After ensuring that TAS models are as close to reality as possible and assuming the same for SBEM analyses - done by independent assessors - it was decided that the reason behind the discrepancy between the results of two assessment tools should be looked up in their process of modelling. By going through all the steps of modelling, the explanation for the discrepancy was found to stem from the two software's different choices for air permeability rate (APR). Air permeability is an indicator of how airtight a building is and is defined as "*air leakage rate per hour per square meter of envelope area at the test reference pressure differential of 50 Pascals*" (UK Government, 2010, p.28). By default, TAS considers this value as 5 $m^3/m^2.h$ @ 50 Pa while for SBEM, it depends on the year of construction. For buildings built before 1995 the value is 25 and for buildings after 1995 the value is 10 $m^3/m^2.h$ @ 50. While some previous studies in TAS have used similarly small air permeability rates (Rotimi *et al.*, 2018; Salem *et al.*, 2018, 2019), Chartered Institute of Building Services Engineers (CIBSE) believes that the value 5 (as employed by TAS) is too optimistic. According to this reference, an air permeability rate of 5 is only achievable for a tight building complying with UK Building Regulation 2013 (CIBSE, 2015).

After identifying this difference, it was decided to run new simulations in TAS using higher APRs, similar to those used in SBEM calculations. By manually changing the APRs in TAS software, the new asset ratings are increased, resulting in changes of EPC bands. As shown in Table 6.5, the new EPCs from TAS are closer to those from SBEM.

Table 6.5 Simulation results with initial and modified APRs

Hotel	**TAS default APR**	**Initial EPC by TAS**	**Updated APR**	**Updated EPC by TAS**	**EPC by SBEM**
Hilton Reading	5	B (50)	10	C (51)	C (57)
DT Dockland	5	C (74)	25	D (82)	E (111)
Hilton Watford	5	B (47)	25	C (53)	C (59)

Despite the changes in APRs, the TAS-generated EPC for DT Docklands is still showing a gap of one band compared to the SBEM calculation, suggesting that the risk of receiving different EPC results is always present, especially if conducted by different assessors using different tools. With regards to assessors' subjective judgment, the risk of differing results seems inevitable. Examples of occasions when relying on subjective assessment may cause different input information into the software tool include but are not limited to deciding on the building fabric construction when there is lack of recorded/reliable information, uncertainty about which NCM activity type to assign to a zone and different ways of measuring the dimensions especially in windows and glazing elements.

Changing the APR is followed by changes in energy consumption. This is caused by the fact that with a larger air permeability rate, the ventilation loses caused by replacement of heated with unheated air is also increased and, in a heating-dominant location, this can increase the energy use for space heating purposes, especially during the colder months of the year, Figure 6.2. This finding is consistent with the works of Ng *et al.* (2013) and Hashemi and Khatami (2015).

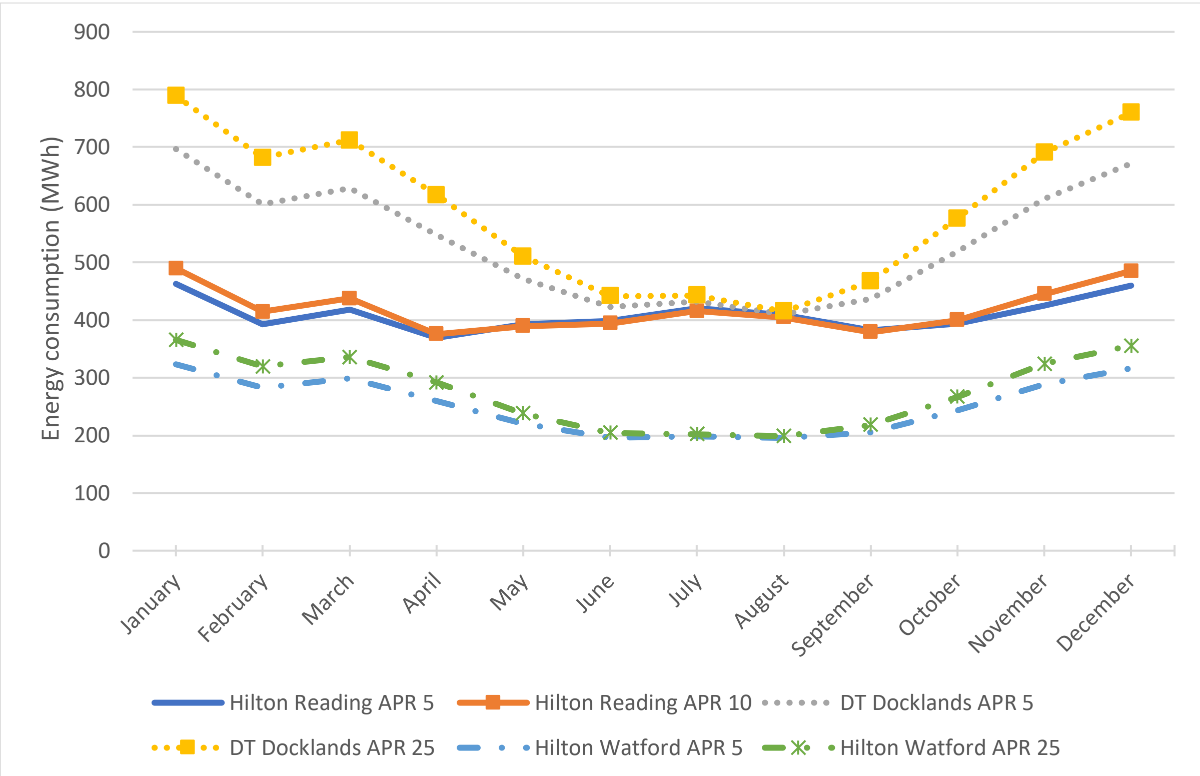


Figure 6.2 Monthly predicted energy consumption with initial and modified APRs

Now, with the increased APRs and the resulting increase in the energy consumption, comparing the simulation results with the measured data shows higher level of overestimation, Table 6.6.

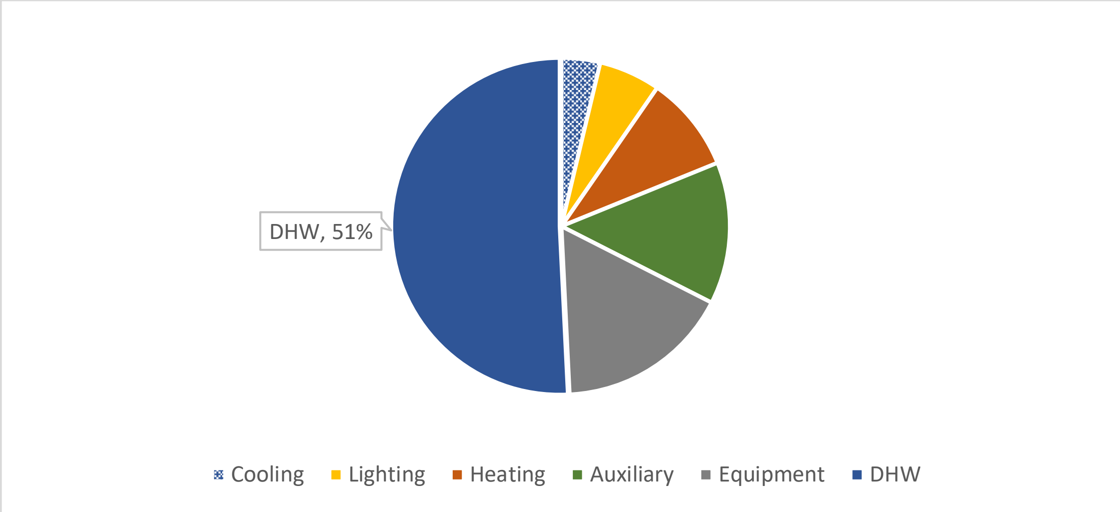
Table 6.6 Validation indicators for simulation results with modified APRs

	Hilton Reading	DT Dockland	Hilton Watford
MBE	-6.3%	25.5%	12.02%
CV(RMSE)	14.1%	28.5%	19.3%

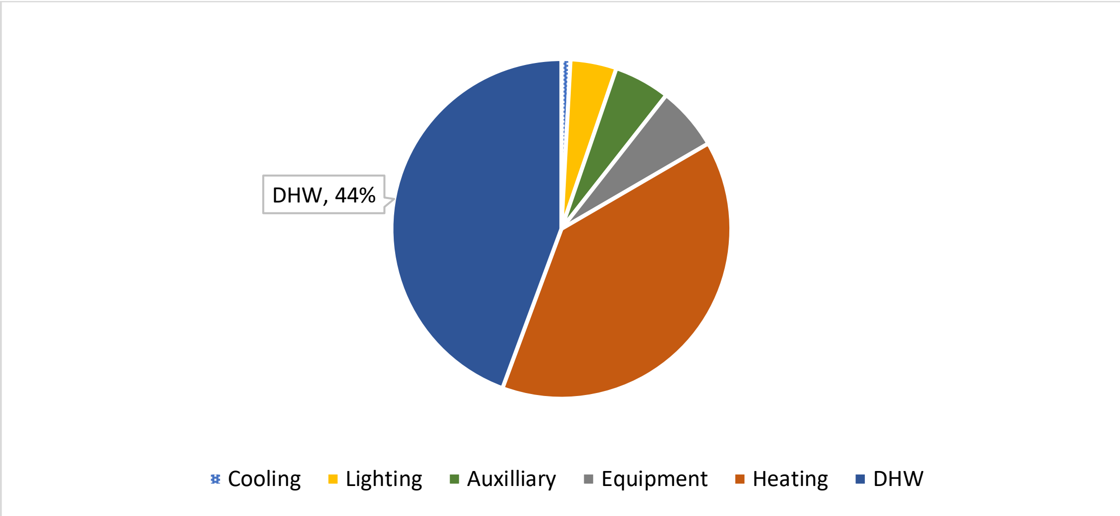
6.3.3 Overestimation of energy consumption and the potential cause

Based on what was shown in Table 6.6, as a consequence of increasing the APR, the overestimation of energy consumption is increased for two of the hotels. This means trying to adopt a more realistic assumption towards energy simulation resulted in an increased gap with measured data for two models. As every effort was taken to ensure that the models are close replications of their corresponding real cases, it would appear that the reason behind this overestimation could be within aspects of EPC calculation that are beyond the control of the assessor. Apart from the intrinsic limitations with modelling and energy simulation tools and methods (Lomas, 1996; Raslan and Davies, 2010; Calama-González *et al.*, 2021), the likely explanation lies in the standard profiles necessary to follow. To pursue this matter further, the breakdown of the estimated energy consumption for each hotel is looked at in Figure 6.3.

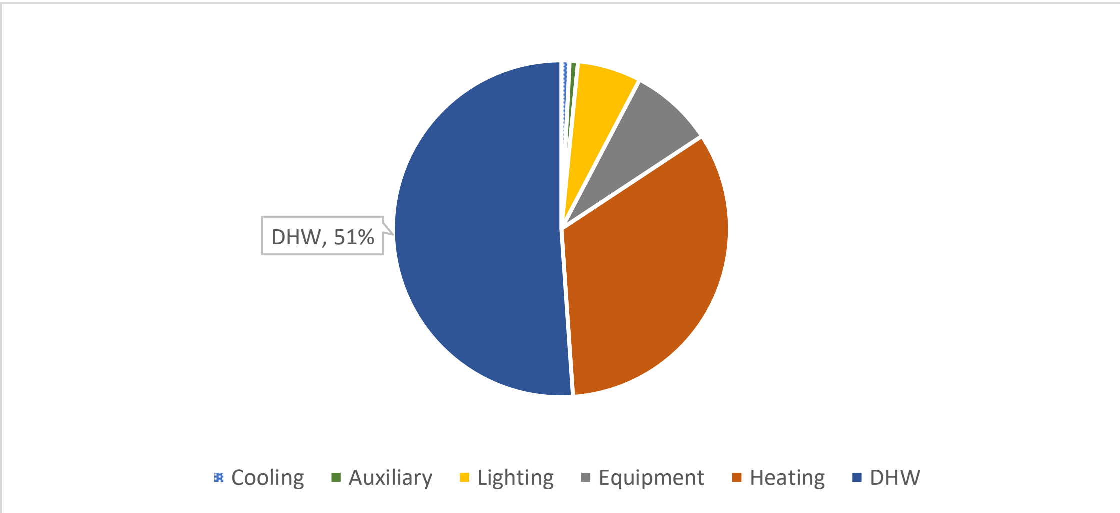
As previously discussed in chapters 4 and 5, the breakdown of energy consumption into end-uses' is based on what is calculated for each hotel according to standard assumptions of NCM Activity database for hotels. This means that what is demonstrated in Figure 6.3 as the share of each end-use is calculated based on what the NCM standard profiles have determined. As demonstrated for all three hotels, around half of the annual predicted energy consumption is consumed for the purpose of DHW. With a minimum efficiency of 91% in each hotel, the water heating system can't be blamed for this high share.



(a) Hilton Reading



(b) DT Docklands



(c) Hilton Watford

Figure 6.3 Estimated energy consumption breakdown for the three hotels

Although the DHW is known to be one of the most energy intensive end-uses in hotels (Hiller and Johnson, 2015, 2017), a share of 44%–51% for DHW seems to be an overestimation. Looking at the existing literature, some of the numbers mentioned as the share of hot water in hotels energy consumption found to be: 15% (Dascalaki and Balaras, 2004) and 17% for a typical hotel in the EU (Styles, Schönberger and Galvez Martos, 2013), 12%–36% for hotels in Balearic Islands (Moiá-Pol *et al.*, 2006), 18% for hotels in Greece (Karagiorgas, Tsoutsos and Moiá-Pol, 2007), 17% for hotels in the US (WTO, 2011) and less than 25% for an average hotel in the UK (Carbon Trust, 2018). Also, CIBSE Guide F sets a benchmark based on energy consumption per bedroom according to type of the hotel. For luxury, business/holiday hotel and small hotel the typical values are 110, 90 and 70 kWh per bedroom (CIBSE, 2012). What is more interesting is that within the same guide, the benchmarks stated for heating in all the three types of hotels are more than twice the size of numbers mentioned for hot water usage (CIBSE, 2012).

As the large share of DHW in the breakdown of estimated energy consumption is calculated by following the NCM standard profiles, it is important to take a look at the guidelines determined for DHW end-use in hotel. The energy demand for DHW in EPC calculation is the energy required to raise the water temperature from 10°C to 60°C based on the demands specified in the NCM Activity database. The activity database defines a daily total figure in l/m^2 per day (DCLG, 2013). For instance, the demand for ensuite guest rooms is 13.12 l/m^2 per day, although in reality the DHW consumption can be highly time-dependant and stochastic (Goldner, 1994; Hendron and Burch, 2007; Pang and O'Neill, 2018). The demand specified for each activity, can be distributed over the day according to the occupancy profile (DCLG, 2013). As there is typically no significant difference between the operations on a weekday and weekend in a hotel, the daily amount of energy use for meeting all the DHW needs remains the same. This results in the monthly DHW energy use only fluctuating based on the number of days in the calendar month, Figure 6.4. The drop in the graphs observed for February is due to the number of days in this month being 28 rather than 30 or 31.

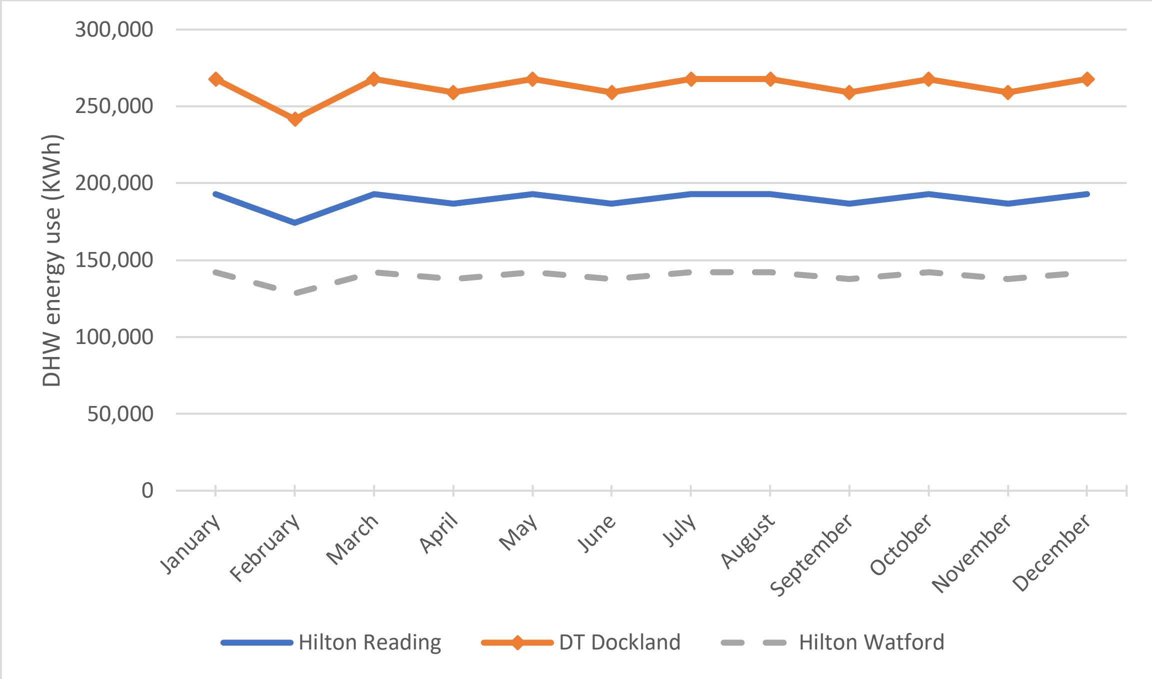


Figure 6.4 Monthly estimated energy consumption for DHW

6.3.4 Evidence for the overestimation of DHW

In the previous section, based on the breakdown of estimated energy consumption and the information from the literature, concerns that the NCM assumptions overestimate DHW in hotels were prompted. In this section, by using information from measured data, empirical evidence is provided to support the existence of this issue

6.3.4.1 Evidence from measured data for water consumption

In order to investigate whether the NCM assumption for hotels' DHW need is an overestimation, it is best to compare it with the measured data. In order to find the amount of hot water consumption estimated by the software based on the NCM guideline, activities identified by NCM in need of DHW are listed with the rate assigned to them in l/d/m². Multiplied by the area covered by each activity and the number of days in a year, the total hot water usage is calculated for each hotel, Tables 6.7–6.9

The measured data for these three hotels provide information about total water consumption, i.e., both hot and cold water. According to the research partner of this study, Hilton, the share of hot water is around 40%–60% of a hotel's total water consumption. By assuming a 50% share for hot water (Murakawa *et al.*, 2007), the annual hot water consumption is illustrated in Table 6.10. The last column in this Table shows the total calculated water consumption acquired from Tables 6.7–6.9.

Table 6.7 Estimated DHW usage for Hilton Reading based on NCM assumption

Activity (NCM database)	DHW need (l/m^2 per day)	Area (m^2)	Number of days	DHW usage (l)
Bedroom	16.238	189.451	365	1,122,823.79
Staff Changing room	120	106.612	365	4,669,605.60
Eat and drink	8	838.511	365	2,448,452.12
Ensuite guest room	13.12	5279.061	365	25,280,367.32
Food preparing	0.33	204.1259	365	24,586.97
Hall	0.6	393.755	365	86,232.35
Office	0.221	697.7627	365	56,285.03
Reception	0.03	418.1075	365	4,578.28
Total				33,692,931.44

Table 6.8 Estimated DHW usage for DT Docklands based on NCM assumption

Activity (NCM database)	DHW need (l/m^2 per day)	Area (m^2)	Number of days	DHW usage (l)
Staff Changing room	120	25.8925	365	1,134,091.50
Eat and drink	8	553.4422	365	1,616,051.2
Ensuite guest room	13.12	9591.523	365	45,931,885.34
Food preparing	0.33	322.4177	365	38,835.21
Hall	0.6	1396.924	365	305,926.25
Office	0.221	259.4117	365	20,925.44
Reception	0.03	370.8936	365	4,061.28
Total				49,051,776.31

Table 6.9 Estimated DHW usage for Hilton Watford based on NCM assumption

Activity (NCM database)	DHW need (l/m^2 per day)	Area (m^2)	Number of days	DHW usage (l)
Staff Changing room	120	38.4047	365	1,682,125.86
Eat and drink	8	487.9439	365	1,424,796.19
Ensuite	13.12	4760.072	365	22,795,032.79

guest room				
Food preparing	0.33	302.737	365	36,464.67
Hall	0.6	633.655	365	138,770.45
Office	0.221	692.198	365	55,836.15
Reception	0.03	228.48	365	2,501.86
Total				26,135,527.97

Table 6.10 Comparing the hotels' measured water consumption with estimated DHW usage

Hotel	Year	Measured water usage (l)	Hot water usage (l) (50% of total)	Estimated hot water usage (l) (by NCM)
Hilton Reading	2016	13,460,974.58	6,730,487.29	33,692,931.44
	2017	13,019,275.41	6,509,637.71	
	2018	13,701,974.12	6,850,987.06	
DT Docklands	2016	38,408,927.46	19,204,463.73	49,051,776.31
	2017	31,395,940.70	15,697,970.35	
	2018	38,084,928.07	19,042,464.03	
Hilton Watford	2016	20,113,962	10,056,981	26,135,527.97
	2017	16,448,968.93	8,224,484.47	
	2018	18,139,103.38	8,812,483.36	

Comparing the numbers in the last two columns, it is clear that what is estimated for hot water consumption within the NCM assumptions, is significantly higher than the actual consumption measured for hotels. This overestimation is so significant that the estimated hot water usage is even more than the total (hot and cold) water consumption measured for each hotel, Table 6.10. This means the NCM's assumption for DHW represent a clear overestimation. Given that the bulk of this estimation comes from guest rooms - see related rows in Tables 6.7–6.9, it is possible that the assumption for guest rooms' DHW needs modifications. Further Tables in Appendix A shows the estimated water consumption for guest rooms with average occupancy (rather than the maximum occupancy considered within NCM Activity database).

6.3.4.2 Evidence from measured data for gas consumption

This overestimation can also be demonstrated in terms of energy consumption. However, separate measurement of energy consumption for different end uses is not a common practice in commercial sector. This has also been raised by Ivanko, Sørensen and Nord (2021) as an issue that needs to be addressed.

The monthly measurement of gas and electricity is available for these three hotels. Therefore, the gas consumption during the hottest time of the year - when there is potentially no or very little space heating demand - was chosen as a base for comparison. Figure 6.5 shows the measured gas consumption for Hilton Watford during 2016–2018. Hilton Watford was chosen as all the DHW for this building is provided by gas-fired boilers, unlike the DT Docklands, where gas-boilers and electric heaters are jointly used for the purpose. DHW in Hilton Reading is also provided through gas-fired boilers but the presence of a swimming pool and high levels of food preparation undertaken on site hinders the ability to isolate gas consumption for DHW.

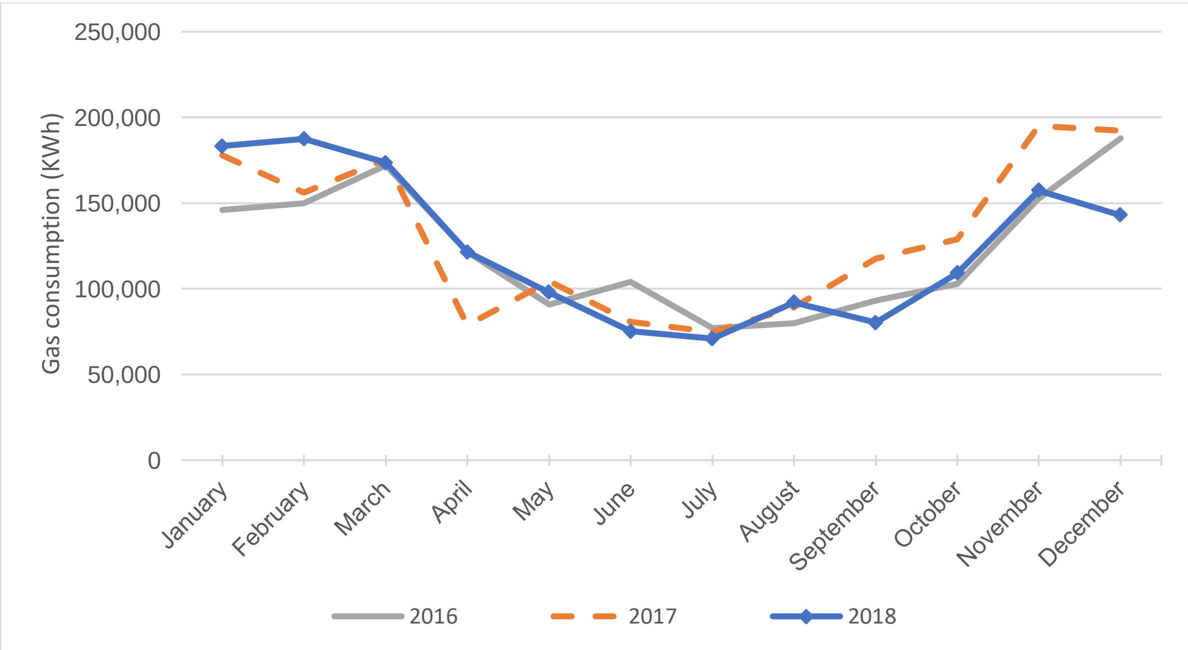


Figure 6.5 Monthly gas consumption for Hilton Watford during 2016–2018

As shown, for all the three years at Hilton Watford, the lowest amount of measured gas consumption is recorded for July, for which the measured numbers are shown in Table 6.11.

Table 6.11 Hilton Watford's gas consumption and occupancy rate for July during 2016–2018

Year	Gas consumption (kWh)	Occupancy rate (%)
2016	77,043.62	87.08
2017	74,772.80	83.89
2018	70,960.03	89.73

As it is very unlikely to have any heating demand during July, it is safe to assume that almost all the gas consumption during July is for water heating purposes, except for a small amount used for kitchen cookers. So, despite measured data showing actual gas consumption in the month of July - over three years - never exceeding 80,000 kWh, the estimated DHW energy use predicted by NCM for July amounts to around 142,000 kWh. Even when gas consumption for July was at its highest for the three years (in 2016), the NCM estimate is almost 84% higher than the actual figure. While it's true that NCM Activity database assumes 100% occupancy, the measured data in Table 6.11 is also for high occupancy rates (ranging from 83% to 89%). For example, the NCM profile assumes an occupancy rate that is just over 13% higher than what the hotel experienced in 2016, but the estimated DHW energy-use is 84% higher than reality. As such, the high occupancy rate used in the NCM assumptions does not appear to explain the disparity between estimated and actual gas consumption. Consequently, it is clear that the NCM assumptions for DHW are significantly overestimated.

6.3.4.3 Evidence from measured data for occupancy rates, heating degree days and energy consumption

In this section, the impact form occupancy rates and heating degree days on monthly energy consumption are investigated. What is understood from these analyses, provides more evidence on the overestimation of DHW by NCM assumptions.

6.3.4.3.1 Hilton Reading

Figure 6.6 compares the monthly occupancy rates and energy consumption for Hilton Reading during the period 2012–2018. As illustrated, their fluctuations are not congruent.

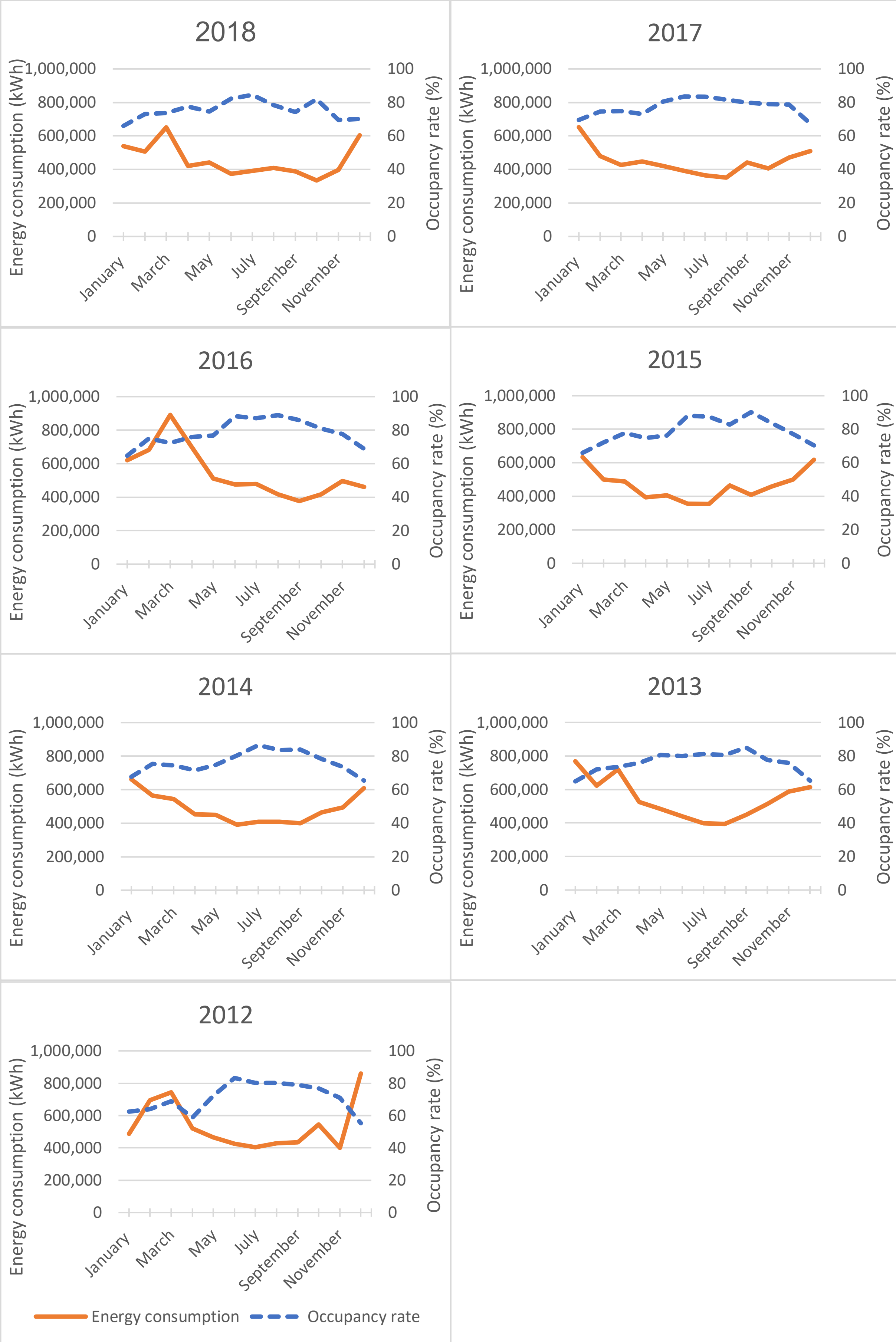


Figure 6.6 Monthly energy consumption and occupancy rates of Hilton Reading during 2012–2018

Higher occupancy rates - in warmer months - are met with reduced energy consumption. Also, during the cold months of January/December, when the energy consumption is usually higher than the rest of the year, the occupancy rates tend to be lower.

With that in mind and a Pearson coefficient of -0.65, it is understood that in this hotel energy consumption and occupancy rates are negatively correlated. However, sudden sharp changes in monthly energy consumption without any noticeable change in the occupancy rates - such as those occurring in November 2012 and March 2016 and 2018 - suggest that changes to occupancy rates cannot explain the fluctuations in monthly energy consumption that well. This is also explainable through regression analysis, where a Coefficient of determination of 0.42 suggests that changes to occupancy rates are only responsible for 42% of fluctuations in monthly energy consumption, Table 6.12.

The next factor known to have an impact on hotels' energy consumption, is the outdoor weather conditions. Here, a factor called heating degree days (HDD) is used as an indicator for external weather. HDD is used to quantify the demand for energy needed in order to heat a building based on the difference between a reference temperature (15.5°C in the UK) and outdoor temperature (CIBSE, 2006). In other words, HDD is a measure of how much – in degrees – and for how long – in days – the outside air temperature was lower than the base temperature. The main implication of HDD is in calculations related to the amount of energy needed for heating a building (BizEE Software, 2021). As expected, HDDs are larger during the colder time of the year. In order to investigate the relationship between the external weather and energy consumption, statistical analysis was carried out, the results of which are also shown in Table 6.12. As illustrated, there is a positive correlation between energy consumption and HDD with a correlation coefficient of 0.72. With a larger coefficient of determination compared to that of occupancy rates, the HDD can better explain the changes in the energy consumption, Table 6.12.

Table 6.12 Statistical analyses for Hilton Reading's energy consumption and independent variables

Variable	Number of observation	Pearson correlation coefficient (R)	Coefficient of determination (R^2)	P-value
Occupancy rates	84	-0.65	0.42	<0.005
HDD	84	0.72	0.52	<0.005

6.3.4.3.1 DT Docklands

Figure 6.7 compares the monthly occupancy rates and energy consumption for DT Docklands during the period 2016–2018. Similar to Hilton Reading, the lines for energy consumption and occupancy rates do not follow similar patterns; higher occupancy rates are met with reduced energy consumption.

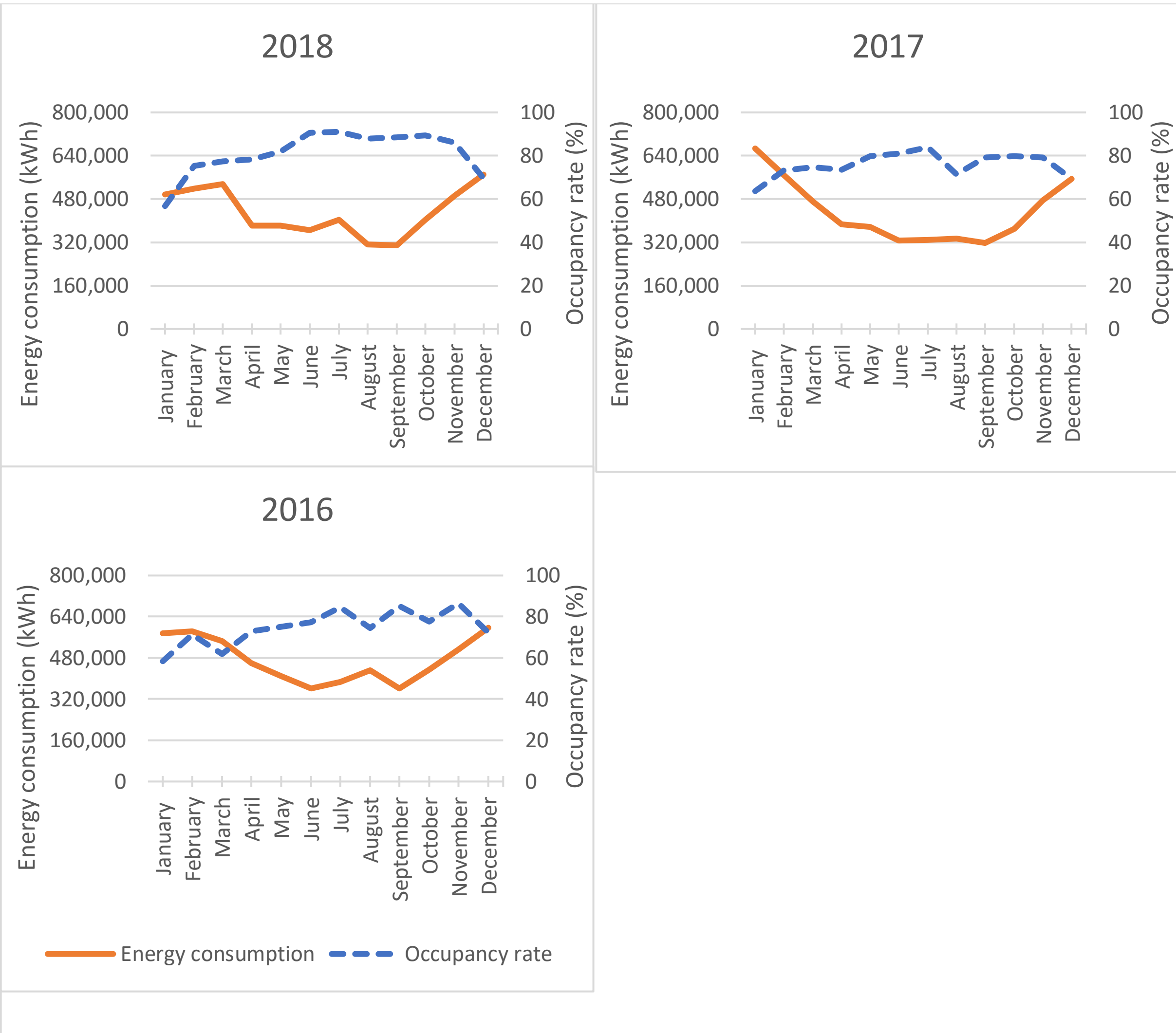


Figure 6.7 Monthly energy consumption and occupancy rates of DT Docklands during 2016–2018

On the other hand, for all the three years, the maximum energy consumption (occurring in December 2016, January 2017, and December 2018) happens when the occupancy rate is lower than that of the summer months. Similar to the previous case, correlation and regression analyses are carried out, results of which are shown in Table 6.13. Again, a negative correlation with occupancy rates and a strong positive correlation with HDD is observed for this hotel's monthly energy consumption. Looking at the R^2 values, it is understood that changes to outdoor temperature can better predict the fluctuations in monthly energy consumption.

Table 6.13 Statistical analyses for DT Docklands' energy consumption and independent variables

Variable	Number of observation	Pearson correlation coefficient (R)	Coefficient of determination (R^2)	P-value
Occupancy rates	36	-0.63	0.40	<0.005
HDD	36	0.87	0.75	<0.005

6.3.4.3.1 Hilton Watford

Figure 6.8 illustrates the monthly occupancy rates and energy consumption for Hilton Watford during the period 2012–2018. Similar to the previous two cases, occupancy rates and monthly energy consumption almost follow opposite patterns; the months with higher occupancy rates tend to have lower energy consumption and the months with highest amount of energy consumption - colder time of the year - have lower occupancy rates. This is also shown through the negative correlation coefficient, Table 6.14.

Similar to the previous two cases, the analyses show that the outdoor weather temperature, represented here by HDD obtains a higher positive correlation coefficient and a higher coefficient of determination, Table 6.14. This suggests that fluctuations in monthly energy consumption is better explained by changes to outdoor temperature.

Figure 6.8 Monthly energy consumption and occupancy rates of Hilton Watford during 2012–2018

Table 6.14 Statistical analyses for Hilton Watford's energy consumption and independent variables

Variable	Number of observation	Pearson correlation coefficient (R)	Coefficient of determination (R^2)	P-value
Occupancy rates	84	-0.73	0.53	<0.005
HDD	84	0.84	0.71	<0.005

Based on the information provided in Figures 6.6–6.8 and Tables 6.12–6.14, a negative correlation was identified between monthly energy consumption and occupancy rates for all the three hotels. Given that the DHW energy use in hotels can vary according to occupancy (Todorović *et al.*, 2020), if the NCM assumptions for hot water consumption were close to reality - and the DHW indeed had the highest share in annual energy consumption - there should have been a rise in energy consumption when the occupancy rates were highest.

Given the positive correlation and higher values for coefficients of determination identified for HDD, it is safe to say that for all the three hotels, end-uses related to outdoor temperature i.e., space heating has a more dominant impact on overall energy consumption, compared to the end-uses more related to the occupancy rate e.g., DHW.

6.4 Discussion

The results and findings of the above paragraphs can be discussed from several different points, which follow as bellow:

6.4.1 Impact of overestimation

Through the process explained in detail in section 6.3, this study found a potential source of overestimation in NCM standard profiles for hotels. This means that the impact of this overestimation can extend beyond the cases introduced in this chapter; it can adversely affect any hotel seeking an EPC in the UK. While some level of uncertainty within assumptions of this kind might be inevitable (van Dronkelaar *et al.*, 2016), significant overestimation or underestimation of energy consumption by EPC can affect its reliability; therefore, these uncertainties should be addressed and avoided. While considerable underestimation of the actual energy consumption can result in failing to meet the expected GHG emission reductions on a national level such as what was discussed in chapter 5, significant overestimation of energy consumption can risk the effectiveness of retrofitting measures (Tigchelaar, Daniels and Menkveld, 2011; Jenkins, Simpson and Peacock, 2017; Ahern and Norton, 2020). As an example, the high share of DHW energy consumption caused by following the NCM profiles can mislead the efforts aimed at improving the EPC and reducing the annual CO_2 emissions. If the efficiency of boilers/electric heaters are increased, this may improve the EPC rating due to the significant share of DHW in estimated annual energy consumption, but in reality, the amount of reduction in CO_2 can be much less as the real share of DHW in the measured energy consumption of the hotel is much less than the predicted amount. As suggested by Gram-Hanssen (2014), with the financial gains being less than what was anticipated, not only the user/owner/manager feels disappointed, but also there is a greater risk of losing trust in the credibility of the scheme altogether.

6.4.2 EPC validation

In line with the previous point, the next issue to be discussed is the lack of validation guidelines specific to the EPC calculations. As discussed, although there are already statistical indicators for validation of performance modelling, there are no guidelines on how to validate an EPC assessment. One can argue that EPCs are essentially tools for policy makers to compare the energy efficiency of similar buildings, attaining an overall view of the levels of energy efficiency in the building sector, without necessarily the need for validation against the measured consumption. While this can be partially true from a policy point of view, the high levels of discrepancies reported in different studies (Cayre *et al.*, 2011; Tigchelaar, Daniels and Menkveld, 2011; Laurent *et al.*, 2013; Balaras *et al.*, 2016; van Dronkelaar *et al.*, 2016; Summerfield *et al.*, 2019) shows that at least from a research point of view this issue should not be overlooked. Furthermore, with the MEES requirement in action, if a building receives markedly different EPC ratings through different assessors/tools, there should be a means of validation to decide which rating is a more accurate reflection of the building's energy performance.

As mentioned, the risk of receiving different EPC ratings for the same buildings has been widely discussed in the context of domestic EPCs. In this study, the same issue was spotted in the context of non-domestic EPCs. After finding the factor contributing to this discrepancy and addressing it, this study proceeded to find a potential source of uncertainty within the current procedure of non-domestic EPC generation in the UK. This source of uncertainty is the NCM's overestimation of DHW. Through the process undertaken here and its results, this study hopes to have made a small contribution to the field of non-domestic EPCs.

6.4.3 Implications of the findings

Future works can investigate whether there are further issues with the assumptions currently used in the UK's EPC scheme and investigate the impact of these potential uncertainties through sensitivity analysis. Meanwhile, the findings of this study can be used to signal that as the NCM guidelines are applied to all the commercial buildings eligible for an EPC, the impact from any major inaccuracy within them could lead to widespread unreliability of EPCs in the sector. It is important to bear in mind that despite the good intentions and concepts behind the MEES requirement, the current procedure in generating EPCs needs further improvement and modification. This is necessary before it can truly contribute to reducing the CO_2 emission in the non-domestic building sector. Steps should be taken to improve the reliability of the EPC scheme for both the policy makers' and the clients' benefit. Avoiding significant underestimation of energy consumption can help to achieve the expected long- term goals in GHG emissions reductions, while avoiding significant overestimation of energy consumption can reduce the risk of non-compliance with MEES requirements and the subsequent penalties.

6.5 Summary and conclusion

This chapter started by investigating the comparability of EPCs generated by different software packages, SBEM and TAS, for three existing hotels. By using the current validation guidelines - aimed at performance modelling rather than compliance modelling - it was demonstrated that the estimated data from TAS for the two hotels with higher levels of discrepancies - DT Docklands and Hilton Watford - were closer to the measured data. Subsequently, it was found that the default value of air permeability rate used by TAS was not realistic and it should be updated with regards to the buildings' age, as does the SBEM analysis. Further simulations with the modified value for air permeability rate resulted in EPCs from the two software packages becoming more consistent, accompanied by higher levels of overestimation for two out of three cases. A breakdown of the energy end uses and comparing it with literature and measured data hinted at a potential overestimation of DHW loads by NCM standard profiles. In order to find evidence on this potential overestimation, measured and predicted data for water and gas consumption were compared. Also, the correlation and regression analyses for monthly occupancy rates and heating degree days were used. The result of all these analyses supported the idea of DHW overestimation by NCM assumptions.

The study continued to discuss that improved reliability and certainty of EPCs are needed for both meeting the expected goals with GHG mitigation policies and compliance with MEES requirement.

Chapter 7 Key factors in determining the EPC rating of hotel buildings

7.1 Statement of the situation

In this chapter, the aim is to find the key parameters with the highest impact on the EPC rating of a hotel. In order to find these parameters, sensitivity analysis is used. Sensitivity analysis is used to determine how different values of an independent variable affect a particular dependent variable under a given set of assumptions. Furthermore, it can also be used to determine how different sources of uncertainty in a mathematical model contribute to the model's overall uncertainty (Kenton, 2020). Through a sensitivity analysis, the parameter whose variations imposes the maximum change on the output results is identified.

In built environment studies, sensitivity analysis has been widely used by researchers to identify parameters with significant impacts on buildings thermal analysis outputs such as annual energy consumption and peak loads (Sun, 2015). For instance, through sensitivity analysis, the parameters with highest impacts on the UK's domestic buildings' EPC rating were found to be central heating system's efficiency, external wall U-value and building geometry (Stone *et al.*, 2014).

There are different techniques for carrying out a sensitivity analysis:

- **Differential sensitivity analysis:** where the input variables are varied a small amount one at a time in order to calculate the local partial derivative of the model output
- **Monte Carlo analysis:** in this technique a series of model runs are performed and for each run, each model input is set to a value selected randomly from a specified probability distribution.
- **Stochastic sensitivity analysis:** in which the inputs are varied at each time step of the dynamic thermal model (Stone *et al.*, 2014)

In this study, differential sensitivity analysis (DSA) - a local sensitivity analysis approach - is employed. Through DSA, only one parameter is changed each time and the rest are kept unchanged. By doing so, any change observed in the simulation outputs can be safely attributed to the change in that specific input parameter (Lam and Hui, 1996).

This chapter begins by choosing the input parameters and their variations for DSA. The choice of parameters is based on the EPCs breakdown of energy consumption for hotel buildings, further discussed in Section 7.3. For each variation of the input data, a new EPC simulation is carried out. The goal of these simulations is to study how changing one parameter's value affects the main outputs in an EPC analysis.

7.2 Materials and methods

7.2.1 Buildings' description

In this study, the three hotels from chapter 6 are studied. While in terms of buildings geometries, location and internal activities, no change has been imposed, but for the purpose of comparability of the buildings and consistency of analyses, some changes have been applied in this study. For example, it is assumed that the buildings share the same type of construction material. Furthermore, some changes to their fixed services are also considered. Tables 7.1 and 7.2 provide further information on these three cases.

Table 7.1 Information about the three hotels

Building	Area (m^2) – Building envelope	Heating/Cooling/DHW
Building 1 (B1)	12,000 m^2 Fully sealed	All areas are covered by fan coil units: • Gas-fired boilers for both heating and domestic hot water. • Chillers for cooling.
Building 2 (B2)	9,500 m^2 Openable windows	• Split/multi split units provide heating and cooling to public areas. • Cooling is not provided to guest rooms. • Electric heaters provide heating to guest rooms. • Electric heaters for domestic hot water.
Building 3 (B3)	17,000 m^2 Openable windows	• Gas-fired boilers for heating. • Chillers for cooling. • Electric heaters for domestic hot water. • Electric heaters are used in the covered bridges connecting the buildings.

Table 7.2 Building fabric construction for the three hotels

Building element	Recommended by	Construction layer	Thickness (mm)
Solid wall	Part L 2006 (E&W)	Concrete 1800 kg/m^3	140
		Air layer	25
		Polyurethan	75
		Plasterboard	13
Flat roof	Part L 2006 (E&W)	Plaster, dense	13
		Concrete roof/floor slab	150
		Polythene	1
		Extruded Polystyrene	160
		Asphalt	19
		Stone chipping	25
Ground Floor	Part L 2002 (E&W)	Flooring screed	50
		Polyurethan	100
		Concrete roof/floor slab	150
		Stone chipping	25
		Clay underfloor	750
Windows: two layers of 4 mm clear glazing with a 6 mm air-filled space (4-6-4), with Low-*E* coating			

7.2.2 Parameters and their range

As discussed in chapter 3, in order to calculate the EPC rating of a hotel (or any other non-domestic building for that matter) two categories of information are needed. The first category is the standard assumptions imposed by NCM Activity database which is specific to the building type. Following the NCM assumptions is mandatory when generating EPCs in the UK. As explained in chapter 3, for the purpose of consistency in comparing buildings with similar use, the NCM Activity database determines internal conditions for each space (or activity) within a building category. An internal condition includes incidental gains from lights, occupants, and equipment as well as heating and cooling set points. Also, system parameters such as metabolic rate for the occupants within that zone, DHW demand, and target room illuminance are all specified by these profiles from NCM Activity database. A comprehensive list of these assumptions for hotels were provided in chapter 3, section 3.3.3.2.

The second category of information includes those specific to the building itself - as opposed to the first category which is specific to the building type. Examples of information from the second category are building size and geometry, weather conditions, building fabric specification, fixed building services and their efficiencies.

As it is mandatory to follow the standard assumptions from NCM Activity database without any change, the parameters from the first category of input data are not considered in the sensitivity analysis.

As it has been discussed in detail in preceding chapters, the estimated energy consumption and CO_2 emission from fixed building services are taken into consideration when calculating the EPC rating. These fixed building services are heating, cooling, auxiliary, lighting and DHW. The sum of CO_2 emissions from these end-uses determines the building's EPC rating.

The emissions from each end-use is calculated by multiplying its energy use by the CO_2 factor for the providing system (grid electricity or natural gas in this study). For example, if heating for a given building is provided through gas-fired boilers, the emissions from this end-use is calculated by multiplying the energy used for space heating in kWh/m^2 by the carbon factor for natural gas in $kgCO_2/kWh$. Carbon factors for different fuels are also assigned by NCM and they are subject to change every few years.

The energy consumption for each of these five end-uses is calculated based on the demand for that end-use and the efficiency of the system providing it. The following list shows the factors considered in calculating the energy consumption and their corresponding category of information.

- Heating and cooling end-use:
    - Heating and cooling set points for each zone (first category).
    - Heat gains from occupants and devices (first category), and lighting (both first and second category as elaborated further below).
    - Heat exchange with external environment dependent on building fabric specification, external weather conditions, air permeability rate (second category).
    - The efficiency of the heating/cooling system (second category).
- Lighting end-use:

- Zones' target illuminance (first category).
  - Amount of daylight/natural light available to the zone (second category).
  - The efficiency of the lighting system (second category).
- DHW end-use:
  - DHW demand for each zone (first category).
  - The efficiency of the DHW system (second category).

As the parameters from the first category cannot be changed, they are not considered here. Table 7.3 shows the individual input data and their variations. For every round of simulation, the input parameter takes a value from the specified range and the EPC calculation is carried out. To compare the impact from changing input values, a base case scenario (BCS) is defined. The value for each parameter in the BCS is selected according to latest recommendations/guidelines by the UK Building Regulations Part L and/or CIBSE Guide A. The BCS value for each parameter is set as the median in the corresponding range.

Table 7.3 Parameters, their variation ranges, and the values in BCS

Parameters	Unit	Variation range	Variation interval	Value in the BCS
External wall insulation thickness	mm	30–120	15	75
Roof insulation thickness	mm	100–220	20	160
Ground floor insulation thickness	mm	40–160	20	100
Glazing U-value	W/m²K	3.28–1.75	~0.25	2.55
Air permeability rate	m³/h.m² @ 50 Pa	2.5–17.5	2.5	10
Heating system efficiency	%	82–100	3	91
		200–500 (for heat pumps)	50	350
Cooling system CoP	-	2–5	0.5	3.5
DHW system efficiency	%	82–100	3	91
Lighting system efficiency	Lm/W	45–75	5	60

For comparability, it is assumed that all three cases share the same specifications for building fabric (unless otherwise specified), air permeability rate, systems' efficiency, and weather type.

7.2.3 Choosing the variation ranges and intervals

The variation ranges defined for each parameter are chosen according to one of the following scenarios:

I. For some of the parameters, apart from a recommended/standard value from the guidelines, there is also a minimum or maximum possible value, either suggested by the guidelines or industry. The standard value is used as the median and the second suggested value (the minimum acceptable or the maximum possible value) serves as either the start or the end of the range. By using these two numbers, i.e., the median and one end of the range, the other end of the range can be calculated. For example, the recommended efficiency for gas-fired boilers is 91% (HM Government, 2013) and the maximum efficiency is considered to be 100%. With maximum and the median determined, the lower end of the range can be calculated by subtracting the difference between median and the maximum from the median value. Returning a figure of 82% as the minimum end of the range.

II. For some of the parameters such as the thickness of the insulation layer, the median value was chosen according to the recommended U-value for external walls, roof, and ground floor in the UK Building Regulation Part L. By checking the values in the software's database of standard construction in England and Wales, the required thickness of thermal insulation for achieving the recommended U-value was selected as the median. By looking at the examples in the database, the minimum thickness of a thermal insulation practically used in the UK for each building element is selected as the lower end of the respective range. The upper end of the range is then calculated based on the lower end and the median value.

The choice of the variation intervals was highly impacted by the small variation range selected for gas-fired boiler's efficiency. As explained, the variation range for this parameter is 82%–100% with a median of 91%. To achieve equal intervals, the possible choices of variation intervals between the median and each end were 1% and 3%. To keep the number of simulations manageable, the latter option was chosen as the variation interval. Choosing this interval results in six simulations for this range with the boilers efficiency being 82%, 85%, 88%, 91% (median value used in the BCS), 94%, 97% and 100%. For comparability, it was decided that for each parameter, the same number of simulations would be conducted. Therefore, the choice of variation intervals for other parameters in Table 7.3 was based on yielding three values between the median and each end of the corresponding range.

7.2.4 Statistical indicators used for sensitivity analysis

As mentioned, in each simulation the input data takes a new value from the range defined for it. The result of each simulation is then compared to that of BCS. Through this, changes in the outputs (i.e., CO_2 emission rate, EPC rating and annual energy consumption) in each simulation are compared with the output values in the BCS. For this purpose, an index called "*change percentage*" is used to measure the change against the BCS, as shown in Equation 7.1.

$$\text{Change percentage} = \frac{v - v_B}{v_B} \text{ x } 100\% \qquad 7.1$$

Where v represents the new output value and v_B refers to that output value in the BCS. A larger change percentage value (in absolute terms) shows a larger change in the output caused by a specific change in an input value.

The change percentage index provides some information on the initial results and illustrates which factors among the list of input data cause larger changes to the outcomes. However, it does not provide any information on the size of change in a given input parameter in order to achieve a specific amount of change in an output. In other words, further information is needed to determine how sensitive the outputs are to the size of change in an input. This information can be obtained through a dimensionless influence coefficient (Lam and Hui, 1996), as shown in Equation 7.2.

$$\mu = \frac{\Delta\text{OP}/OP_B}{\Delta\text{IP}/IP_B} \qquad 7.2$$

Where μ is the influence coefficient (IC), ΔOP and ΔIP denote the change of output and input, respectively, and OPB and IPB refer to the output and input values in the BCS, respectively. A larger value of the IC (in absolute terms) signals a more sensitive relation between the input and output changes (Sun, 2015).

7.3 Results

7.3.1 Base case scenario for three hotels

To achieve the aim of this research, numerous rounds of simulations were carried out. In each simulation, an input parameter took a new value from the range specified in Table 7.3 and the impacts on the three main outputs, i.e., EPC rating, CO_2 emission rate, and the energy consumption were observed. Table 7.4 shows the results for the BCS for each building.

Table 7.4 Base case scenario (BCS) results for the three hotels.

Hotel	EPC rating	CO_2 emission (kg/m^2) per year	Annual energy use (kWh/m^2)
B1	B (47)	88.71	300.23
B2	C (65)	121.54	234.18
B3	D (85)	168.78	396.85

Looking at Table 7.4, it is worth mentioning that, despite having less annual energy consumption, B2 has a worse EPC rating compared to B1. This is caused by the fact that the EPC rating depends on the CO_2 emission rate (DCLG, 2013) and as discussed in section 7.3.2, CO_2 emission rate of a building also depends on the energy use of fixed building services and the carbon factors for their corresponding systems' type of fuel.

At the time of running this study, the factors for grid electricity and natural gas in the commercial sector – assigned by NCM and mandatory to follow – are 0.519 and 0.216 $kgCO_2e/kWh$, respectively. Therefore, in B2, as all the systems work with electricity, despite having lower levels of energy consumption compared to B1 (where electricity and natural gas are used jointly), the CO_2 emissions are higher than B1. Higher CO_2 emission rate is translated to less favourable EPC rating for B2. In order for the input parameters to take all the values defined for them (see Table 7.3), in total more than 150 simulations were carried out for the three hotels. The results of which are discussed in the following sections.

7.3.2 Simulation results for Building 1

Based on the number of input parameters for Building 1, 48 simulations were carried out for this hotel. The results of these simulations, the input parameters undergoing a change in that simulation and the corresponding parameter's value in the base case scenario are all demonstrated in Table 7.5. Furthermore, the results of the simulation using the change percentage index are illustrated in Figure 7.1. As explained, the change percentage index compares the changes in the outputs of each simulation with the output values in the BCS.

Table 7.5 Input parameters, BCS outputs and simulation results for Building 1

Simulation	**Input parameter**	**EPC rating**	**CO_2 emission (kg/m^2)**	**Energy consumption (kWh/m^2)**
Parameter: External wall thermal insulation thickness (mm)				
S1	30	B (48)	89.1	303.33
S2	45	B (47)	88.88	301.74
S3	60	B (47)	88.77	300.81
BCS	**75**	**B (47)**	**88.71**	**300.23**
S4	90	B (47)	88.67	299.82
S5	105	B (47)	88.64	299.52
S6	120	B (47)	88.62	299.28
Parameter: Roof thermal insulation thickness (mm)				
S7	100	B (47)	88.92	301.62
S8	120	B (47)	88.82	301
S9	140	B (47)	88.76	300.55
BCS	**160**	**B (47)**	**88.71**	**300.23**
S10	180	B (47)	88.67	301.62
S11	200	B (47)	88.64	301
S12	220	B (47)	88.62	300.55
Parameter: Ground floor thermal insulation thickness (mm)				
S13	40	B (47)	88.47	300.96
S14	60	B (47)	88.57	300.55
S15	80	B (47)	88.65	300.35
BCS	**100**	**B (47)**	**88.71**	**300.23**
S16	120	B (47)	88.76	300.15
S17	140	B (47)	88.8	300.09
S18	160	B (47)	88.83	300.06
Parameter: Glazing U-value ($W/m^2.K$)				
S19	3.28	B (50)	94.08	313.19
S20	3.02	B (50)	93.68	310.83

S21	2.8	B (50)	93.45	309.38
BCS	**2.55**	**B (47)**	**88.71**	**300.23**
S22	2.3	B (47)	88.31	297.97
S23	2.08	B (47)	87.47	295.99
S24	1.75	B (48)	89.89	297.01
Parameter: Air permeability rate ($m^3/h.m^2$ @ 50 Pa)				
S25	2.5	B (48)	89.14	293.78
S26	5	B (47)	88.46	294.35
S27	7.5	B (47)	88.33	296.26
BCS	**10**	**B (47)**	**88.71**	**300.23**
S28	12.5	B (48)	89.37	304.77
S29	15	B (49)	90.22	309.9
S30	17.5	B (49)	91.2	315.39
Parameter: Boiler efficiency (heating and DHW systems) (%)				
S31	82	B (50)	93.96	324.52
S32	85	B (49)	92.09	315.87
S33	88	B (48)	90.34	307.78
BCS	**91**	**B (47)**	**88.71**	**300.23**
S34	94	B (47)	87.18	293.15
S35	97	B (46)	85.75	286.54
S36	100	B (45)	84.41	280.31
Parameter: Cooling system CoP				
S37	2	B (50)	93.73	309.9
S38	2.5	B (49)	91.39	305.39
S39	3	B (48)	89.82	302.38
BCS	**3.5**	**B (47)**	**88.71**	**300.23**
S40	4	B (47)	87.87	298.61
S41	4.5	B (47)	87.22	297.36
S42	5	B (46)	86.7	296.36
Parameter: Lighting system efficacy (Lm/W)				
S43	45	B (49)	92.23	306.1
S44	50	B (48)	90.8	303.69
S45	55	B (48)	89.66	301.78
BCS	**60**	**B (47)**	**88.71**	**300.23**
S46	65	B (47)	87.91	298.91
S47	70	B (47)	87.24	297.83
S48	75	B (46)	86.65	296.89

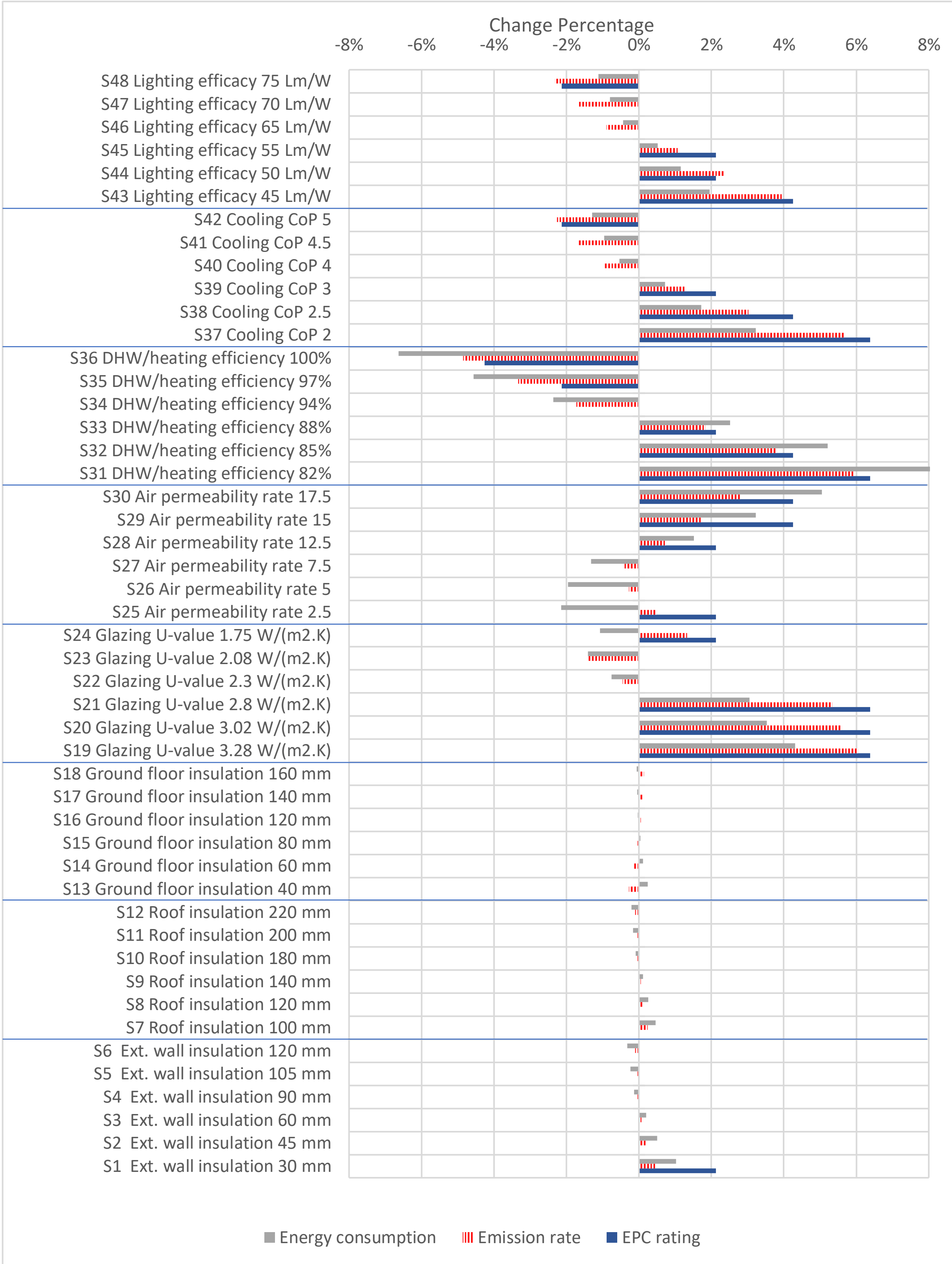


Figure 7.1 Simulation results for B1 using change percentage index

As shown in Table 7.5 and Figure 7.1, changing the U-value of solid elements – caused by changing the thickness of the thermal insulation layer – has an almost negligible impact on the EPC rating, energy consumption and CO_2 emission rate of this building, simulations S1–S18. However, an interesting pattern is observed for S13– S15 (when the thickness of thermal insulation in ground floor is reduced). In S13, reducing the thickness of insulation layer in ground floor, results in heating and auxiliary energy use to increase by 6.4% and 0.1%, respectively, while cooling energy use is reduced by 10.7%. While in terms of energy consumption, the increase in heating and auxiliary energy uses offsets the reduction in cooling energy use, the situation for CO_2 emission is different. Due to the considerable difference between the carbon factors for grid supplied electricity and natural gas, i.e., 0.519 and 0.216 kg/kWh, respectively, the reduction in cooling-induced emissions outweighs the increase caused by the other two end-uses. The same pattern applies to S14 and S15.

As large areas of the building's façade are covered in glazing (window to wall ratio for this building is 0.6), it is no surprise that changing the glazing U-value results in relatively large changes. However, it seems the impacts are more significant for simulations S19–S21, where higher U-values are adopted for glazing compared to the BCS. The higher U-values are mostly caused by removing the Low-*E* film from the glazing element, Table 7.6. Due to increased heat loss and increased heat gain caused by removing the Low-*E* film (see chapter 4 for information on low-*E* coatings), both heating and cooling energy consumption are increased, followed by an increase in auxiliary energy consumption – due to change in the peak loads – resulting in a larger change in the outputs. Therefore, the impacts are more noticeable compared to simulations S22–S24.

Table 7.6 Type of glazing used in the sensitivity analysis, simulations 19 – 24:

Simulation	**Type of glazing**	**U-value (W/m².K)**
S19	4-6-4, uncoated glass, air filled	3.28
S20	4-6-4, uncoated glass, Argon filled	3.02
S21	4-12-4, uncoated glass, air filled	2.8
S22	4-20-4 Low-*E* glass, SF6 filled	2.3
S23	4-6-4 Low-*E* glass, Argon filled	2.08
S24	4-12-4-12-4 uncoated glass, Argon filled	1.75

In most of the simulations, an improvement in an input parameter e.g., increasing a system's efficiency, results in negative change percentages in energy use and emission rate, denoting a reduction in these two outputs. Usually, it is expected to observe that a reduction in energy consumption is followed by reduction in emission rate and sometimes in EPC rating (changes to EPC rating remains 0 in some simulations). However, simulations S24 and S25 do not follow this pattern. Here, despite a reduction in energy use, the emission rate and EPC rating are increased. The reason is similar to what was explained for S13.

In simulation S24, the glazing U-value is set to 1.75 $W/m^2.K$, achieved by using a triple-layered glazing, whereas the value in the BCS is 2.55 $W/m^2.K$. This change results in reducing the heating energy consumption by almost 29%. However, it also causes an increase of 19.5% and 8.4% in cooling and auxiliary energy consumption, respectively. With the carbon factor for grid electricity being much higher than that of natural gas, the increase in emissions caused by extra cooling and auxiliary energy use outweighs the reduction in emissions caused by reduced energy consumption for heating. Therefore, despite a reduction in energy consumption, the emission rate is increased as is the EPC rating. The same pattern happens in simulation S25, where a very low air permeability rate, 2.5 $m^3/h.m^2$ @ 50 Pa, results in 39% reduction in heating, followed by a 48% increase in cooling energy consumption.

In simulations S31–S48, the results are as expected: lower systems' efficiencies result in increased values for the three outputs while improvements in output results - negative change percentages - are caused by higher efficiencies. Furthermore, it is understood that changes to boilers efficiency - providing both heating and DHW for this building - cause higher changes on the three outputs, simulations S31–S36.

7.3.3 Simulation results for Building 2

Table 7.7 shows the input variations and results for 60 simulations carried out for Building 2. Figure 7.2 shows these results through the change percentage index. For this building, larger changes are observed from changing the thickness of thermal insulation, compared to B1. This is due to solid elements covering a larger share of external surfaces (the building has a window to wall ratio of 0.11). Still, the change percentage is still not considerable. With the low share of glazing in this building, the small impact on the outputs from changing the U-value of glazing elements is expected.

Table 7.7 Input parameters, BCS outputs and simulation results for Building 2

Simulation	**Input parameter**	**EPC rating**	**CO_2 emission (kg/m^2)**	**Energy consumption (kWh/m^2)**
Parameter: External wall thermal insulation thickness (mm)				
S1	30	C (66)	124.63	240.14
S2	45	C (65)	123.07	237.12
S3	60	C (65)	122.15	235.35
BCS	**75**	**C (65)**	**121.54**	**234.18**
S4	90	C (64)	121.1	233.35
S5	105	C (64)	120.78	232.72
S6	120	C (64)	120.53	232.24
Parameter: Roof thermal insulation thickness (mm)				
S7	100	C (65)	122.46	235.97
S8	120	C (65)	122.06	235.18
S9	140	C (65)	121.76	234.61
BCS	**160**	**C (65)**	**121.54**	**234.18**
S10	180	C (64)	121.36	233.83
S11	200	C (64)	121.21	233.55
S12	220	C (64)	121.1	233.33
Parameter: Ground floor thermal insulation thickness (mm)				
S13	40	C (65)	122.45	235.94
S14	60	C (65)	121.99	235.04
S15	80	C (65)	121.71	234.52
BCS	**100**	**C (65)**	**121.54**	**234.18**
S16	120	C (64)	121.41	233.94
S17	140	C (64)	121.32	233.76
S18	160	C (64)	121.25	233.63
Parameter: Glazing U-value ($W/m^2.K$)				
S19	3.28	C (65)	122.23	235.53
S20	3.02	C (65)	121.87	234.82
S21	2.8	C (65)	121.65	234.39
BCS	**2.55**	**C (65)**	**121.54**	**234.18**
S22	2.3	C (64)	121.2	233.54
S23	2.08	C (64)	120.9	232.95
S24	1.75	C (64)	120.31	231.81
Parameter: Air permeability rate ($m^3/h.m^2$ @ 50 Pa)				
S25	2.5	C (62)	115.94	223.4

S26	5	C (63)	118.22	227.78
S27	7.5	C (64)	119.64	230.53
BCS	**10**	**C (65)**	**121.54**	**234.18**
S28	12.5	C (65)	123.32	237.61
S29	15	C (66)	125.17	241.19
S30	17.5	C (67)	127.07	244.84
Parameter: Guest rooms' heating system efficiency (%)				
S31	82	C (65)	122.47	235.98
S32	85	C (65)	122.14	235.34
S33	88	C (65)	121.83	234.74
BCS	**91**	**C (65)**	**121.54**	**234.18**
S34	94	C (64)	121.27	233.65
S35	97	C (64)	121.01	233.16
S36	100	C (64)	120.77	232.7
Parameter: Public spaces heating system efficiency				
S37	2	C (65)	122.62	236.26
S38	2.5	C (65)	122.11	235.29
S39	3	C (65)	121.78	234.64
BCS	**3.5**	**C (65)**	**121.54**	**234.18**
S40	4	C (64)	121.36	233.83
S41	4.5	C (64)	121.22	233.56
S42	5	C (64)	121.1	233.34
Parameter: DHW system's efficiency (%)				
S43	82	C (70)	131.51	253.39
S44	85	C (68)	127.96	246.55
S45	88	C (66)	124.63	240.14
BCS	**91**	**C (65)**	**121.54**	**234.18**
S46	94	C (63)	118.65	228.62
S47	97	C (62)	115.93	223.38
S48	100	C (62)	113.37	218.45
Parameter: Cooling system CoP				
S49	2	C (66)	123.76	238.46
S50	2.5	C (65)	122.72	236.46
S51	3	C (65)	122.03	235.13
BCS	**3.5**	**C (65)**	**121.54**	**234.18**
S52	4	C (64)	121.17	233.47
S53	4.5	C (64)	120.88	232.91
S54	5	C (64)	120.65	232.47
Parameter: Lighting system efficacy (Lm/W)				
S55	45	C (66)	124.34	239.58
S56	50	C (65)	123.21	237.39

S57	55	C (65)	122.29	235.63
BCS	**60**	**C (65)**	**121.54**	**234.18**
S58	65	C (64)	120.91	232.96
S59	70	C (64)	120.37	231.94
S60	75	C (64)	119.92	231.05

As mentioned in Table 7.1, in this building, cooling systems are not provided in guest rooms thus, although changes in some of the input parameters result in an increase in cooling load, the final increase in cooling energy use is not significant. An example of this can be observed in simulation S25 where a significant reduction in air permeability rate reduces the heating energy consumption considerably. This is similar to what happens in B1 but, unlike that building, there is not a significant increase in cooling energy consumption. Here, the only increase in the cooling energy consumption comes from the public areas, e.g., the reception, the lounge, the halls, etc. In this building, the space heating and DHW are provided through different systems. The impact of DHW system's efficiency on the output results becomes more obvious in this building when the results of S43–S48 are compared with those of S31–S36 (changing the efficiency of guest rooms heating system), Figure 7.2. Despite inflicting changes of the same size (efficiency range of 82%–100% with intervals of 3%), the impacts from changing the DHW system efficiency are much higher.

7.3.4 Simulation results for Building 3

Table 7.8 shows the input variations and results for 54 simulations carried out for Building 3. Figure 7.3 shows these results through the change percentage index. Again, the impact from changing the thickness of the thermal insulation layer in solid elements is almost negligible, especially when the changes are applied to the ground floor and roof. Among the remaining factors, changes made to lighting and cooling systems' efficiency resulted in less than ± 2% changes in the outputs compared to the BCS. Similar to both B1 and B2, changes applied to the DHW system's efficiency, i.e., simulations S37–S42, generate a higher percentage of change on the three outputs.


Change Percentage
-8%
-6%
-4%
-2%
0%
2%
4%
6%
8%
10%
S60 Lighting efficacy 75 Lm/W
S59 Lighting efficacy 70 Lm/W
S58 Lighting efficacy 65 Lm/W
S57 Lighting efficacy 55 Lm/W
S56 Lighting efficacy 50 Lm/W
S55 Lighting efficacy 45 Lm/W
S54 Cooling CoP 5
S53 Cooling CoP 4.5
S52 Cooling CoP 4
S51 Cooling CoP 3
S50 Cooling CoP 2.5
S49 Cooling CoP 2
S48 DHW system efficiency 100%
S47 DHW system efficiency 97%
S46 DHW system efficiency 94%
S45 DHW system efficiency 88%
S44 DHW system efficiency 85%
S43 DHW system efficiency 82%
S42 Public zones heating efficiency 5
S41 Public zones heating efficiency 4.5
S40 Public zones heating efficiency 4
S39 Public zones heating efficiency 3
S38 Public zones heating efficiency 2.5
S37 Public zones heating efficiency 2
S36 Guest rooms heating efficiency 100%
S35 Guest rooms heating efficiency 97%
S34 Guest rooms heating efficiency 94%
S33 Guest rooms heating efficiency 88%
S32 Guest rooms heating efficiency 85%
S31 Guest rooms heating efficiency 82%
S30 Air permeability rate 17.5
S29 Air permeability rate 15
S28 Air permeability rate 12.5
S27 Air permeability rate 7.5
S26 Air permeability rate 5
S25 Air permeability rate 2.5
S24 Glazing U-value 1.75 W/(m2.K)
S23 Glazing U-value 2.08 W/(m2.K)
S22 Glazing U-value 2.3 W/(m2.K)
S21 Glazing U-value 2.8 W/(m2.K)
S20 Glazing U-value 3.02 W/(m2.K)
S19 Glazing U-value 3.28 W/(m2.K)
S18 Ground floor insulation 160 mm
S17 Ground floor insulation 140 mm
S16 Ground floor insulation 120 mm
S15 Ground floor insulation 80 mm
S14 Ground floor insulation 60 mm
S13 Ground floor insulation 40 mm
S12 Roof insulation 220 mm
S11 Roof insulation 200 mm
S10 Roof insulation 180 mm
S9 Roof insulation 140 mm
S8 Roof insulation 120 mm
S7 Roof insulation 100 mm
S6 Ext. wall insulation 120 mm
S5 Ext. wall insulation 105 mm
S4 Ext. wall insulation 90 mm
S3 Ext. wall insulation 60 mm
S2 Ext. wall insulation 45 mm
S1 Ext. wall insulation 30 mm
Energy consumption
Emission rate
EPC rating

Figure 7.2. Simulation results for B2 using change percentage index

Table 7.8 Input parameters, BCS outputs and simulation results for Building 3

Simulation	Input parameter	EPC rating	CO_2 emission (kg/m^2)	Energy consumption (kWh/m^2)
Parameter: External wall thermal insulation thickness (mm)				
S1	30	D (86)	171.06	406.48
S2	45	D (85)	169.87	401.59
S3	60	D (85)	169.19	398.67
BCS	**75**	**D (85)**	**168.78**	**396.85**
S4	90	D (85)	168.51	395.56
S5	105	D (84)	168.3	394.61
S6	120	D (84)	168.14	393.86
Parameter: Roof thermal insulation thickness (mm)				
S7	100	D (85)	169.08	398.06
S8	120	D (85)	168.95	397.54
S9	140	D (85)	168.85	397.15
BCS	**160**	**D (85)**	**168.78**	**396.85**
S10	180	D (85)	168.72	396.61
S11	200	D (85)	168.67	396.41
S12	220	D (85)	168.63	396.26
Parameter: Ground floor thermal insulation thickness (mm)				
S13	40	D (85)	169.12	398.51
S14	60	D (85)	168.95	397.69
S15	80	D (85)	168.85	397.18
BCS	**100**	**D (85)**	**168.78**	**396.85**
S16	120	D (85)	168.73	396.61
S17	140	D (85)	168.69	396.4
S18	160	D (85)	168.66	396.26
Parameter: Glazing U-value ($W/m^2.K$)				
S19	3.28	D (87)	173.72	409.68
S20	3.02	D (87)	173	406.31
S21	2.8	D (87)	172.53	404.1
BCS	**2.55**	**D (85)**	**168.78**	**396.85**
S22	2.3	D (84)	167.96	393.03
S23	2.08	D (84)	167.32	390.09
S24	1.75	D (84)	168.01	387.85
Parameter: Air permeability rate ($m^3/h.m^2$ @ 50 Pa)				
S25	2.5	D (83)	164.95	379.59

S26	5	D (83)	166.08	384.68
S27	7.5	D (83)	167.22	389.78
BCS	**10**	**D (85)**	**168.78**	**396.85**
S28	12.5	D (85)	170.09	402.36
S29	15	D (85)	171.6	408.67
S30	17.5	D (87)	173.25	415.31
Parameter: Heating system efficiency (%)				
S31	82	D (86)	171.56	409.67
S32	85	D (86)	170.53	404.89
S33	88	D (85)	169.56	400.43
BCS	**91**	**D (85)**	**168.78**	**396.85**
S34	94	D (84)	167.82	392.37
S35	97	D (84)	167.03	388.71
S36	100	D (83)	166.29	385.28
Parameter: DHW system's efficiency (%)				
S37	82	D (90)	179.26	416.69
S38	85	D (88)	175.48	409.41
S39	88	D (86)	171.96	402.62
BCS	**91**	**D (85)**	**168.78**	**396.85**
S40	94	D (83)	165.59	390.35
S41	97	D (82)	162.7	384.78
S42	100	D (80)	159.98	379.55
Parameter: Cooling system CoP				
S43	2	D (86)	170.75	400.29
S44	2.5	D (85)	169.78	398.41
S45	3	D (85)	169.13	397.16
BCS	**3.5**	**D (85)**	**168.78**	**396.85**
S46	4	D (84)	168.32	395.6
S47	4.5	D (84)	168.05	395.08
S48	5	D (84)	167.83	394.67
Parameter: Lighting system efficacy (Lm/W)				
S49	45	D (86)	171.65	401.23
S50	50	D (85)	170.45	399.24
S51	55	D (85)	169.47	397.61
BCS	**60**	**D (85)**	**168.78**	**396.85**
S52	65	D (84)	167.98	395.15
S53	70	D (84)	167.4	394.19
S54	75	D (84)	166.9	393.37

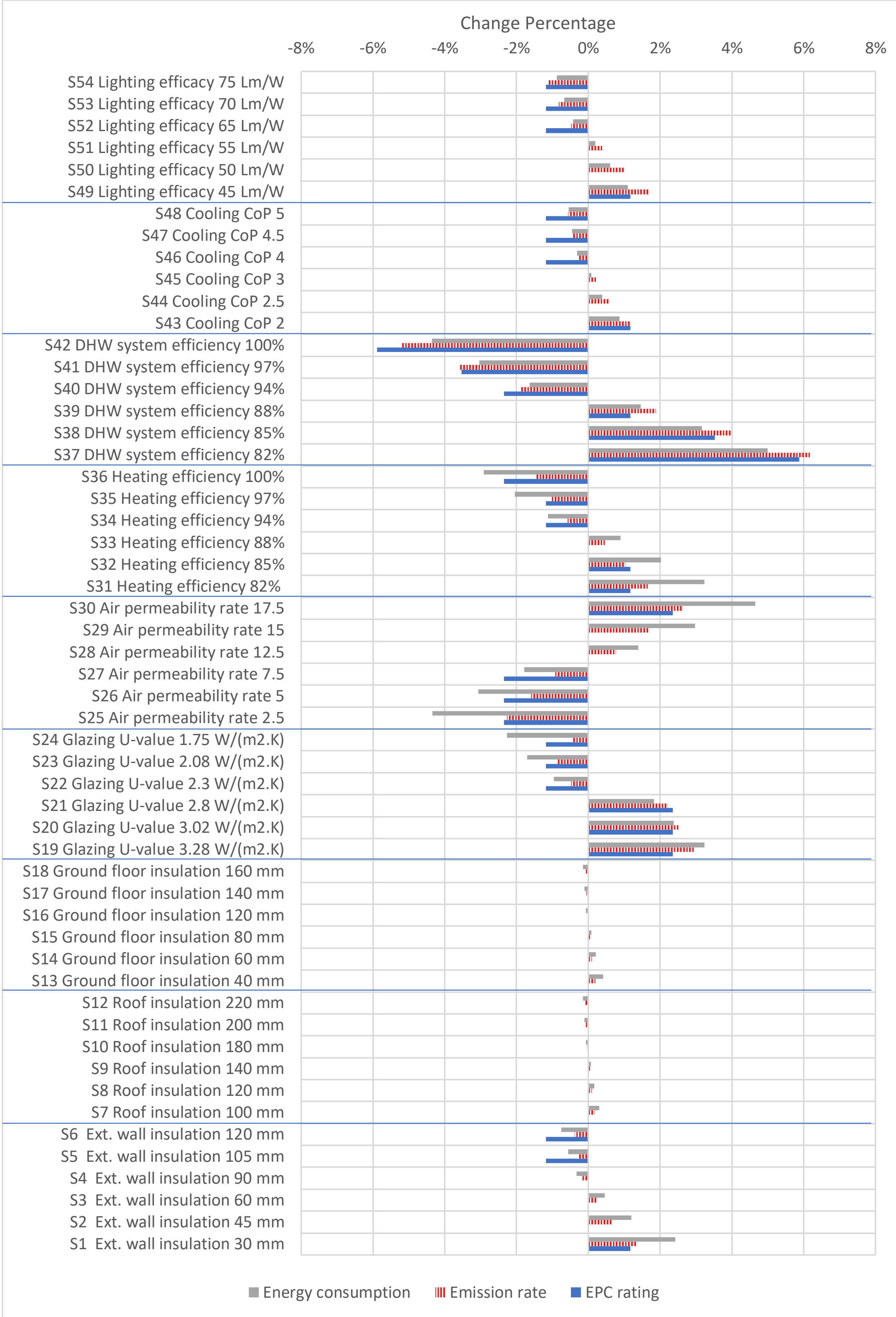


Figure 7.3 Simulation results for B3 using change percentage index

7.3.5 Impact of the type of fuel

As shown in Tables 7.5, 7.7 and 7.8 and Figures 7.1–7.3, very change to any input value is followed by changes to both emission rate and energy use. However, changes to the EPC rating are less frequent. B1 has 26 simulations with 0% change in the EPC rating while B2 and B3 each have 22. Given the total number of simulations for each building, the frequency of a change in EPC rating for cases B1, B2 and B3 is 46%, 64% and 60%, respectively. As the buildings underwent the same changes, the reason behind more frequent EPC changes in B2 and B3 can be attributed to their fuel type. In B1, the main fuel is natural gas, in B2 grid electricity is the only fuel, and in B3, despite using both natural gas and grid electricity, the latter is the main fuel. With a higher CF for grid electricity and the EPC rating's dependence on emission rates, it is obvious that having electricity as the dominant fuel results in more frequent changes to the EPC rating compared to when the main fuel is natural gas. This shows that beyond the impact of single parameters, the type of fuel – with regards to the assigned carbon factors – needs to be taken into consideration.

7.3.6 Influence Coefficient

As explained in section 7.2.4, despite providing some initial information, the change percentage index does not demonstrate how sensitive the outputs are to the size of the change in input parameters. Information of this kind are provided through influence coefficient index (see Equation 7.2). Figures 7.4–7.6 illustrate the average influence coefficient for different parameters. As shown, in all three cases, the DHW system's efficiency has the largest absolute IC value. This means that the relationship between the DHW system's efficiency and the three outputs is the most sensitive, compared to other parameters.

For B2 and B3 - where heating and DHW are provided by separate systems - the heating system's efficiency has the second largest IC value. The glazing U-value also has high IC values for B1 and B3, where the window to wall ratio is 0.3 and above. Among the rest of the parameters, the sensitivity of the outputs to lighting system's efficacy, air permeability rate and cooling system's CoP is relatively small. Also, it is obvious from the Figures 7.4–7.6 that the sensitivity of outputs to the U-value of the solid elements - represented by the thickness of the thermal insulation layer - is negligible.

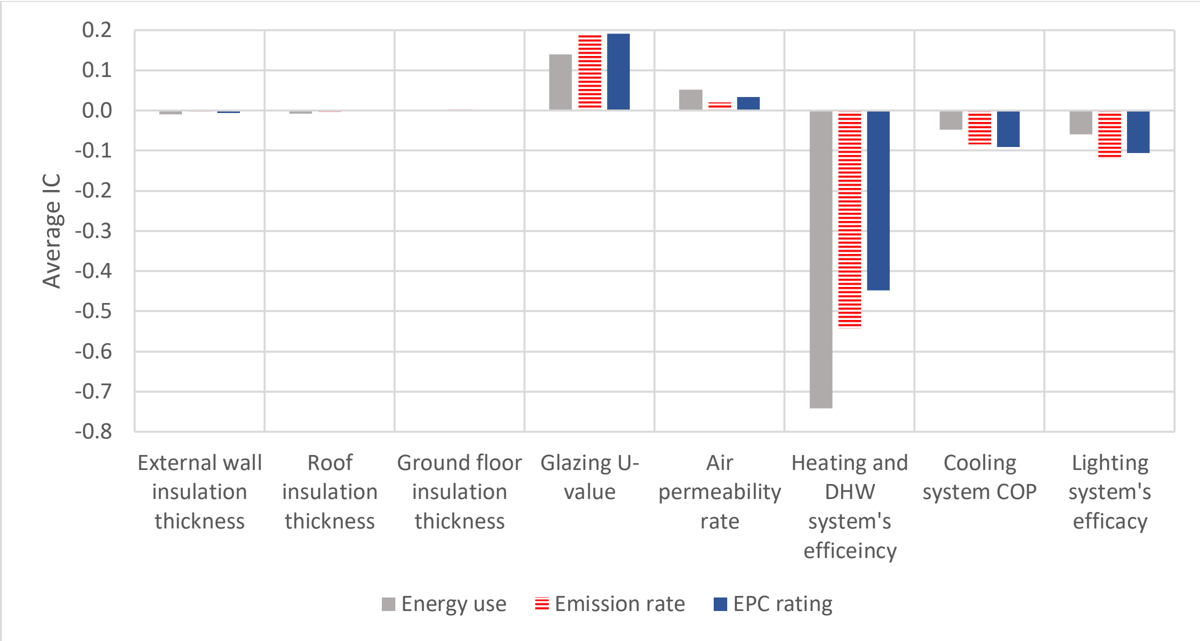


Figure 7.4. Average influence coefficient for Building 1.

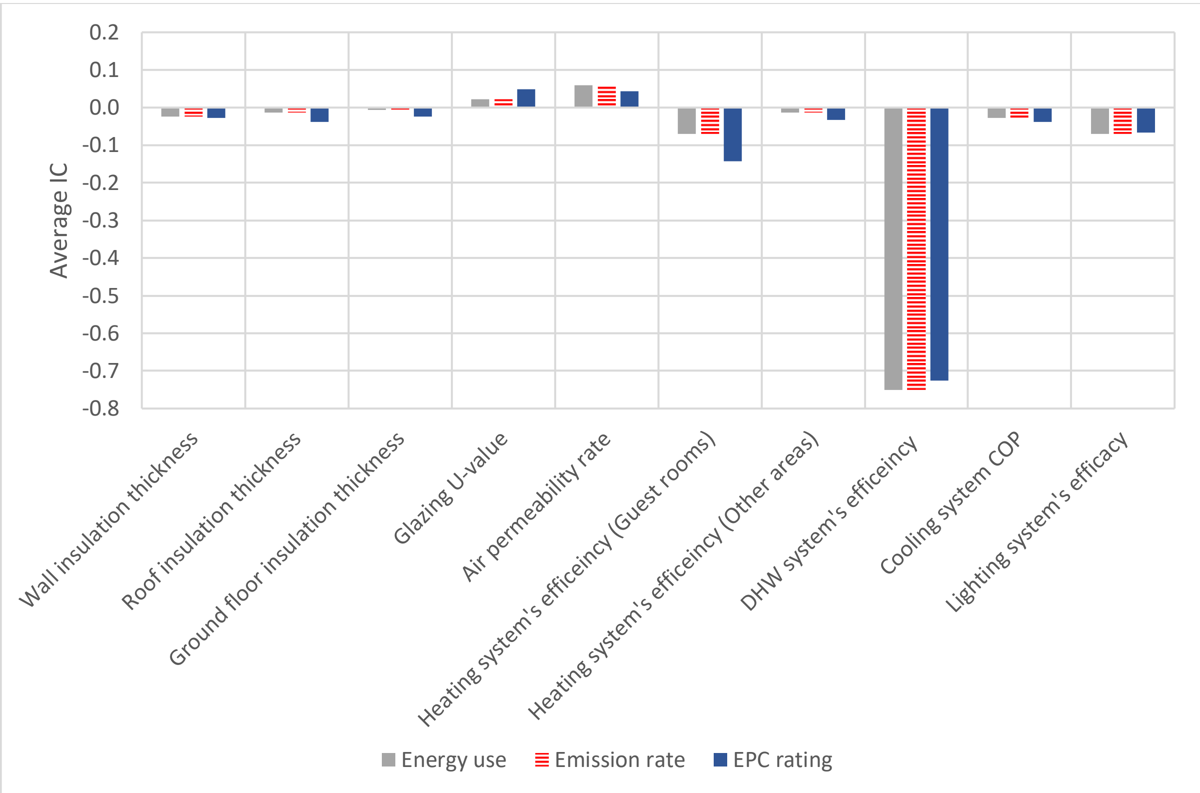


Figure 7.5. Average influence coefficient for Building 2.

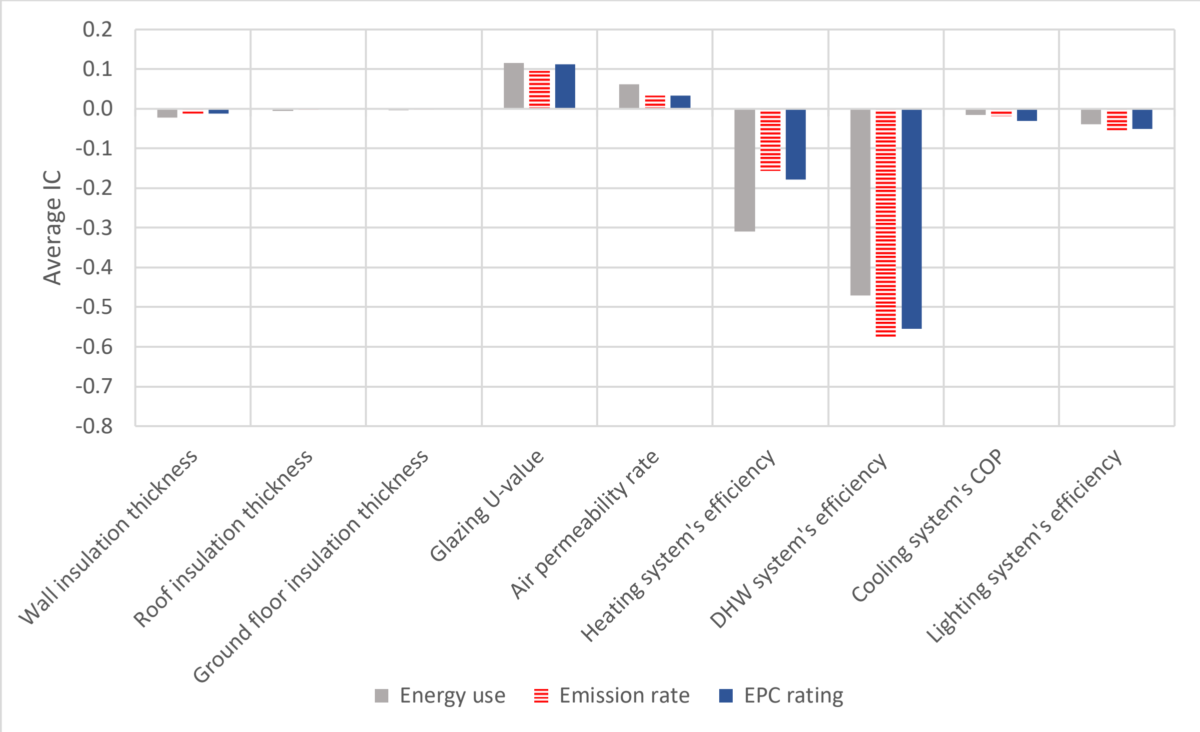


Figure 7.6. Average influence coefficient for Building 3.

7.4 Discussion

The findings of this study suggest that, within the current existing procedure for EPC calculation, DHW system's efficiency is a key factor in determining a hotel's EPC rating. With regards to the role of carbon factors in determining the emission rate, and hence the EPC rating, the DHW system's efficiency can have a bigger impact on the EPC rating when grid electricity is used for DHW provision. As mentioned already, these impacts are subject to change upon further amendments to the carbon factors by NCM.

Furthermore, although there are different parameters from the second category of information – information specific to the building specification, see section 7.2.2 – that affect the heating energy consumption of a hotel, the study results suggest that the efficiency of the heating systems is the second key factor in determining the EPC rating of a hotel.

While parameters such as lighting system's efficacy, glazing U-value, air permeability rate and cooling system's CoP have a relatively small impact compared to DHW and heating system's efficiency, the current results suggest that buildings' solid fabric U-values come with almost no tangible impact on the EPC results.

Depending on the audience, the findings of this study can have different implications. From the energy assessor point of view, the findings can be used to determine which parameters' data need to be collected and entered in the EPC analysis tool with more precision. While some levels of uncertainty may be inevitable in any sort of simulation tool (van Dronkelaar *et al.*, 2016) – as all the input data may not always be available – the results of the current study suggests that uncertainties about the building's DHW and/or heating systems' efficiency are more detrimental to the outcome of an EPC calculation. On the other hand, uncertainties about the solid elements' U-value can cause less adverse impact on the EPC rating.

From another point of view, the findings of this study are especially helpful for clients/hoteliers when they need to undertake measures to improve their buildings' EPC rating. If a considerable change in the EPC rating is needed, then parameters that EPC rating is more sensitive to, should be considered, i.e., improving the efficiency of DHW and/or heating systems. If these measures are not applicable, given the lesser sensitivity of EPC rating to other parameters such as lighting or cooling systems' efficiencies, the required change in the EPC might only be achievable through a combination of several different measures, which should be simulated and analysed on its own. To that end, improving the thermal performance of the solid elements by increasing the thermal insulation will hardly have any noticeable impact on the EPC rating.

The results of the study in this chapter should also be looked at alongside the learnings from chapter 5 and 6. The findings of this study suggests that if a hotel is facing penalties due to noncompliance with the MEES, then increasing the efficiency of its DHW system will potentially improve the EPC rating considerably, so much so that the MEES requirements will be met. However, the findings of chapter 6 suggested that due to DHW being highly overestimated, the expected benefits from improving the efficiency of DHW system (in terms of reducing energy consumption, CO_2 emissions and energy costs) may not be achieved, as suggested by Jenkins, Simpson and Peacock (2017) and Ahern and Norton (2020). Now, the message for some of the stakeholders could be that: increase the efficiency of DHW system in your hotel to avoid facing a penalty regardless of how much reduction in CO_2 emissions will be realised.

The findings of this chapter suggest that improving the efficiency of cooling systems may not improve the EPC rating considerably. While based on the study results in chapter 5, the cooling end-use is probably underestimated for hotels meaning that although in terms of compliance with MEES, increasing the efficiency of cooling systems may not be that helpful, but the actual savings in energy consumption and CO_2 emission can be much higher.

The above two paragraphs highlight the fact that what was expected from MEES may not be realised in hotel sector unless these issues in the current procedure of non-domestic EPCs for hotels are rectified.

7.5 Summary and conclusion

This study was carried out to identify the key parameters in the current procedure of non-domestic EPCs for hotels in England and Wales through a differential sensitivity analysis on three existing hotels. This was achieved by breaking down the energy consumption predicted by the current EPC procedure into five main end-uses: heating, cooling, auxiliary, DHW and lighting. The parameters affecting each of these were listed and further refined by dividing them into two categories of data. The first included those mandatory to follow as per requirements of NCM and the second included those related to building specific characteristics, which were therefore admissible for change. By looking at the recent regulations and regulatory documents, a base case value was selected for each of those parameters from the second category of information. This value was then assigned as the median to form a range of smaller and larger values used for the sensitivity analysis. Numerous rounds of simulations were carried out for each of the buildings. In each simulation only one input data was changed and the impacts on the EPC rating, CO_2 emissions, and energy use were compared against the base case scenario. By using the influence coefficient, the study shows that, within the current accepted procedure of EPC generation, the outputs are most sensitive to the DHW and heating system's efficiency parameters. The findings can be valuable in different ways for both EPC assessors and clients.

Chapter 8 Scottish EPC

8.1 Statement of the situation

The EPC scheme that has been used and discussed in all previous chapters applies to buildings in England and Wales. Non-domestic buildings in Scotland also require an EPC rating after the completion of the construction work or when the building is sold or rented. Despite notable similarities, there are some important differences between the Scottish and the English version of the EPC. The key impact of these differences is that if the same building is assessed by both English and Scottish EPC, it will receive a less favourable rating from the latter scheme. This may be the reason that the MEES requirement does not apply to Scottish EPC. However, other restrictions are in place for buildings with seemingly poor ratings, such as agreeing to have their energy consumption measured and monitored on a monthly basis.

In this chapter, a hotel from Edinburgh, is studied. Assessed under the Scottish scheme, the hotel receives a poor EPC band. While it should be noted that the hotel - being in Scotland - is not subject to the limitation of the MEES, a low rating can still have negative implications for its image. As such the practical importance of an EPC rating is still significant to all stakeholders.

In this chapter, measures for improving the hotel's EPC rating with regards to the findings of chapters 6 and 7 are applied. Furthermore, the framework within which the Scottish EPC is generated is explained and compared with the English versio.

8.2 Scottish EPC

8.2.1 Similarities with English EPC

The Scottish EPC has some significant similarities with the English EPC. These are:

- They both have a rating system from A to G, with A being the most energy efficient and G showing the poorest energy performance.
- They are both generated by procedures that convert the building's calculated loads into energy and hence CO_2 emission using seasonal efficiency parameters.
- They both rate a building's performance based on its CO_2 emission.

- They both follow the NCM Activity database, setting default values for occupancy, temperature set points, outdoor air rates, heat gain profiles and hot water demand for each type of space in the building.

8.2.2 Differences with English EPC

Despite communalities between the two schemes, there is one particularly significant difference. As explained in depth in chapter 3, the English EPC uses a Reference building's emission rate to calculate the Standard emission rate. Then by using a normalising factor and dividing the Actual building's emission rate by the standard emission rate, the asset rating is calculated (see chapter 3, section 3.2.2). Then based on the value of asset rating (AR) the EPC band is defined as shown in Table 8.1. With this procedure, it can be understood that the English EPC is <u>not</u> a linear carbon scale.

Table 8.1 EPC bands defined based on asset rating (AR) in <u>English</u> EPC scheme

Scale	**EPC Band**
$0.00 \leq$ **AR** ≤ 25.0	A
$25.0 <$ **AR** ≤ 50.0	B
$50.0 <$ **AR** ≤ 75.0	C
$75.0 <$ **AR** ≤ 100.0	D
$100.0 <$ **AR** ≤ 125.0	E
$125.0 <$ **AR** ≤ 150.0	F
$150.0 <$ **AR**	G

The Scottish EPC does not use a Reference building. It relies on the emission rate from the actual building to calculate a rating, as illustrated in Table 8.2. This means that unlike the English version, the Scottish EPC is based on a linear carbon scale derived from the actual building. Due to this difference in methodology the English and Scottish EPC are <u>not</u> directly comparable, as a building can receive a much better EPC rating within the English scheme compared to the exact same building being assessed through the Scottish Scheme.

Another difference between these two schemes is concerned with their use of weather files. As discussed, the English EPC uses TRY weather file from a station closest to the location of the building, drawing from the list of 14 stations available from CIBSE (CIBSE, 2017b). For the Scottish EPC, the Glasgow TRY weather file is used regardless of the building's geographical whereabouts.

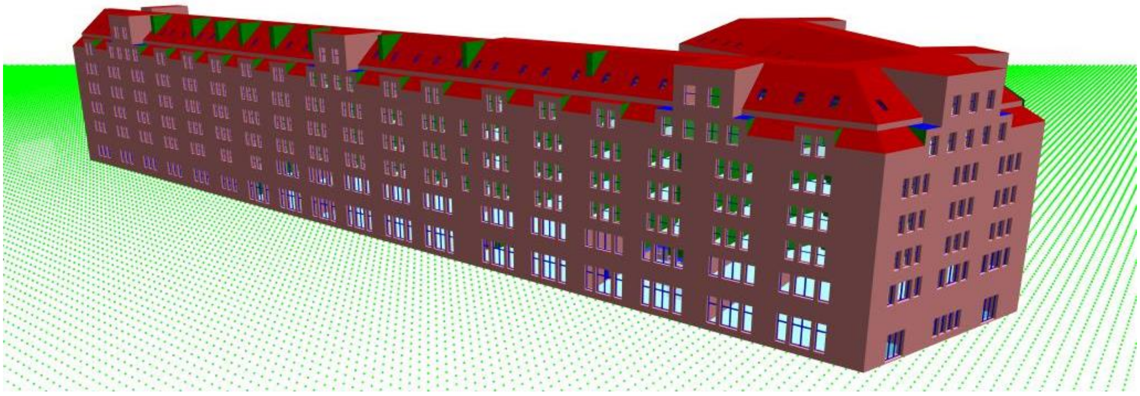
Table 8.2 EPC bands defined based on the CO_2 emission rates in Scottish scheme

CO_2 Emission (kg CO_2 per m^2 per year)	EPC Band
0 to 15	A
16 to 30	B
31 to 45	C
46 to 60	D
61 to 80	E
81 to 100	F
>100	G

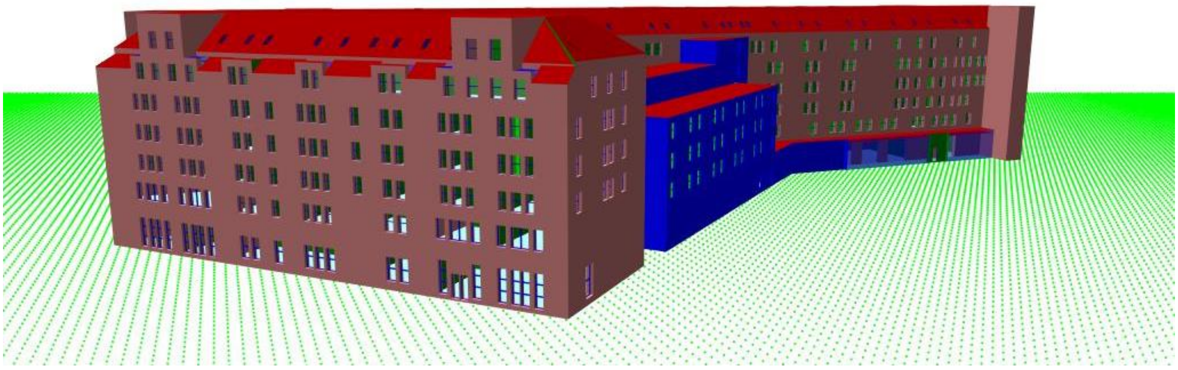
8.3 Building description

8.3.1 Building geometry and fabric

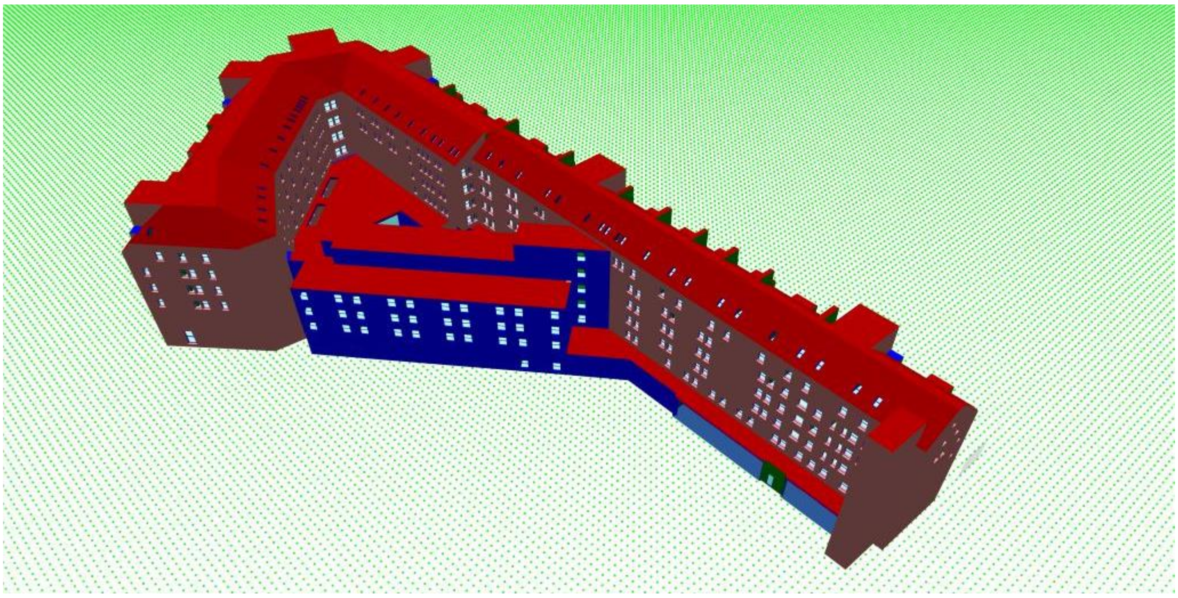
The hotel is located in Edinburgh, and it is comprised of two buildings. The main building is a historic building from early 1900s, and a smaller building was added later, around 30 years ago. The total floor area is around 18,380 m^2. The main building has five floors above the ground floor and a basement accommodating areas such as changing rooms, kitchen, offices, etc. The ground floor accommodates a lounge, a main restaurant, several smaller restaurants and bars, swimming pool and gym, and halls/suites. The levels above ground floor are primarily occupied by guest rooms. The newer section of the complex has fewer floors, accommodating its guest rooms in three levels. The hotel complex has a total of 270 guest rooms. Neither of the two buildings are sealed, meaning that the windows are openable. The older part has a stone construction while the newer part is made of brick cavity walls. The windows are mostly wooden framed, openable single-layered glazing, without any coatings. The windows dimensions are also varied, however, the windows in the newer section tend to be smaller than those in the main building. Views to the building's geometry is provided in Figure 8.1.



(a) View to main entrance and the longer wing



(b) View to shorter wing



(c) Aerial view to the hotel, showing the newer part in blue

Figure 8.1 Views to the hotel geometry

8.3.2 Building services

Heating and cooling are provided to all spaces, through gas-fired boilers and chillers. Heating and cooling to the guest rooms are distributed through fan coil units. The DHW is provided through gas-fired calorifiers. The hotel also benefits from a combined heat and power (CHP) system that serves areas such as guest rooms and swimming pool. The lighting system is mainly LED while some areas are covered by compact fluorescent lamps.

8.4 Modelling assumptions

As the hotel is subjected to the Scottish EPC, the Glascow TRY weather file is used. According to this weather file, the minimum and maximum outdoor temperature are -7 and 25.1°C, occurring on December 28th and July 9th, respectively. Figure 8.2 shows the hourly outdoor temperature in this weather file.

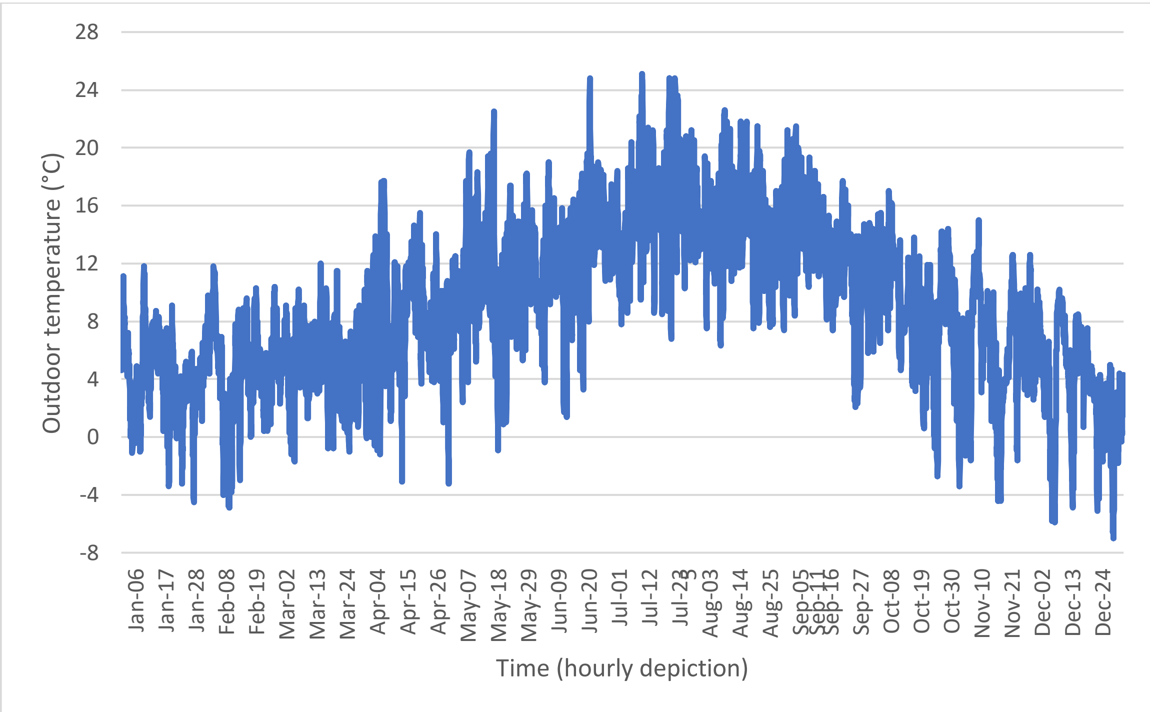


Figure 8.2 Hourly outdoor temperature in Glasgow TRY weather file, reproduced from the weather file by (CIBSE, 2017b)

Comparing the graph in Figure 8.2 with that of London TRY - see chapter 4, Figure 4.3 - shows that the number of hours in a year with the outdoor temperature below 15.5°C - the reference temperature in the UK below which it is assumed that the building needs heating and above which there would be cooling demand - is much higher. Judging based on the hourly outdoor temperature graphs, the number of hours in a year with the outdoor temperature below 15.5°C is 7778 for Glasgow and 6423 for London. Given the total number of hours in a year, 8760, this means that with the Glasgow TRY weather file, almost 89% of the hourly outdoor temperatures are below 15.5°C while for London weather file, this number is around 73%. Knowing this and given that the building fabric is very leaky, even before running the simulation it can be expected that space heating holds a high share of the hotel's energy consumption breakdown.

Based on the information collected during the site visit and the common constructions at the time - based on NCM's database for construction - the building fabric specifications are shown in Table 8.3. Due to the buildings' age, the air permeability rate of the building is considered 25 $m^3/(h.m^2)$ @ 50 Pa.

Table 8.3 Building fabric specification considered for the simulation.

Building element	**Construction**	**Calculated area-weighted average U-value (W/m²K)**
External wall	Historic part: Stone construction	0.79
	Newer part: Cavity Wall, consisting of two layers of brick separated with a layer of wool quilt of 50 mm thickness	0.55
Ground floor	Historic part: Solid floor consisting of clay underfloor, brick slips, concrete/cement	1.14
	Newer part: Solid floor consisting of thick layer of soil and concrete slab	1.07
Roof	Historic part: Pitched roof consisting of roof tiles, cold loft space and wool quilt	0.95
	Newer part: Flat roof consisting of stone chipping, asphalt, extruded polystyrene, polythene and concrete slab	0.45
Window	4 mm Single glazing	5.13

8.5 Results

8.5.1 Baseline model

By carrying out the Scottish EPC calculation, the building in its current situation acquired an EPC rating of band E, with the CO_2 emission rate of 76 kg/m^2 per year. The total energy consumption is calculated as 458.87 kWh/m^2. This number is net of the electricity displaced by the CHP and also not inclusive of the equipment energy use.

Figure 8.3 shows the share of each end use in the annual energy consumption of the hotel, estimated by TAS using the building characteristics and NCM standard profiles. As always, the DHW holds the highest share among other end-uses. As seen in the graph, the DHW and space heating's share add up to 89% of total energy consumption. The share of cooling end-use is not 0, but as it is very small i.e., 2.05 kWh/m^2 - less than 0.5% - it appears as 0 in the graph.

The reason behind the high share of DHW is partly due to the potential overestimation of guest rooms' DHW demand by the NCM standard profiles - discussed in full in chapter 6. As guest rooms take up approximately 8250 m^2 - around 43% of total floor area - the impact of this overestimation becomes considerable. Due to the heating dominant weather situation and the building fabric's leaky state, the high share of space heating energy consumption is not unexpected.

With the DHW and space heating energy use showing the highest shares (Figure 8.3) and following the findings of chapter 7, in order to improve the hotel's EPC, the focus should be on measures causing a reduction in energy use and/or CO_2 emission of one of these two. These measures are improving the thermal performance of the glazing elements, applying air source heat pump (ASHP) for space heating, and trying different cogeneration systems.

8.5.2 Comparing the simulated data with measured data

Similar to previous chapters, the simulated energy consumption of the hotel is compared with the measured data from the recent years, Figure 8.4.

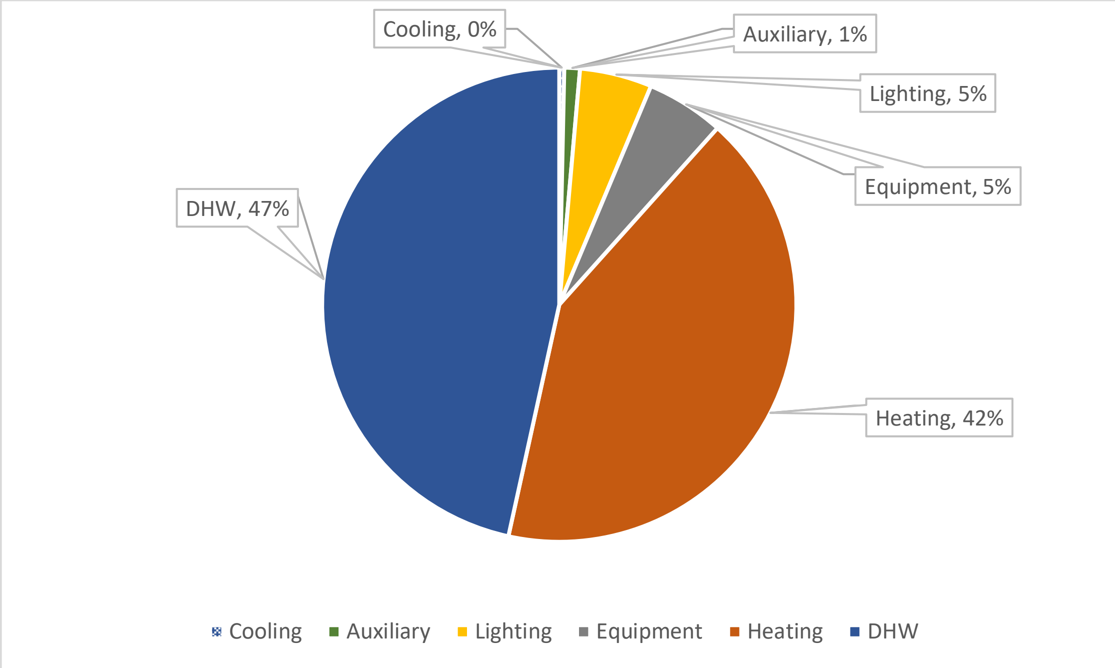


Figure 8.3 Share of end uses in annual estimated energy consumption.

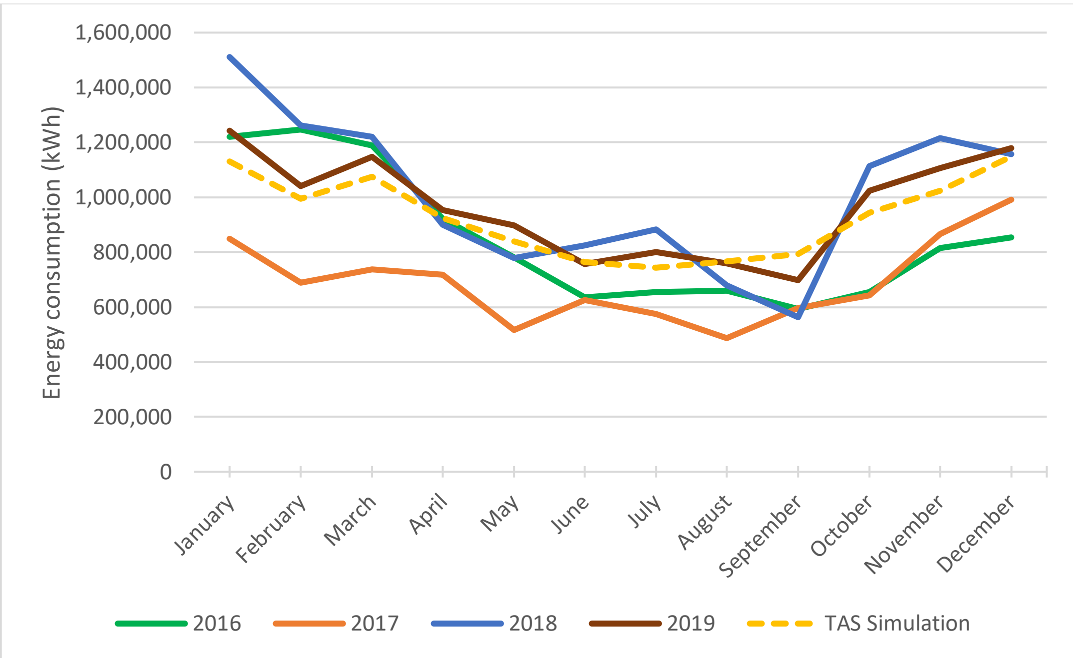


Figure 8.4 Comparing the simulation result with measured data

The hotel's energy consumption changes from one year to another, with the monthly fluctuations being very different for each year. However, similar to cases in previous chapters, due to a heating dominant climate, the energy consumption tends to be higher during the colder time of year i.e., January–March and October–December.

Compared to the measured data, the simulated energy consumption fluctuates less intensely from one month to another. As discussed in previous chapters, it can be partly due to the normalised nature of TRY weather files. This has been fully discussed in section 4.6.2. Similar to what was carried out in chapter 6, regression analysis was performed to investigate the relation between monthly measured energy consumption and HHD and occupancy rate during 2015–2019, the results of which are illustrated in Table 8.4. Consistent with the findings of chapter 6, the monthly energy consumption is negatively correlated with the occupancy rate and positively correlated with HDD. Given the values for coefficient of determination, the HDD can better explain the changes to monthly energy consumption. This finding on the impact from external weather conditions on the hotel's energy consumption is consistent with literature, examples of which were mentioned in section 2.1.1.

Table 8.4 Statistical analyses for energy consumption and independent variables

Variable	Number of observation	Pearson correlation coefficient (R)	Coefficient of determination (R^2)	P-value
Occupancy rates	60	-0.55	0.30	<0.005
HDD	60	0.73	0.54	<0.005

Looking back at Figure 8.4, the energy consumption for 2017 seems to be much lower compared to the other years. Looking at the monthly HDD and occupancy rates, Figure 8.5, it can be observed that despite following similar patterns, the annual HDD for 2017 is by average 5% less than that of other years. While this can partly justify the reduced energy consumption, it is also possible that the catering activities have been fewer over that year.

Before proceeding further, it should be mentioned that data for 2020 was also available, but due to the extraordinary conditions of the Pandemic in that year - causing zero occupancy rates during April–June and extremely low rates for the rest of the year - it was decided not to include the data for this year in the graph.

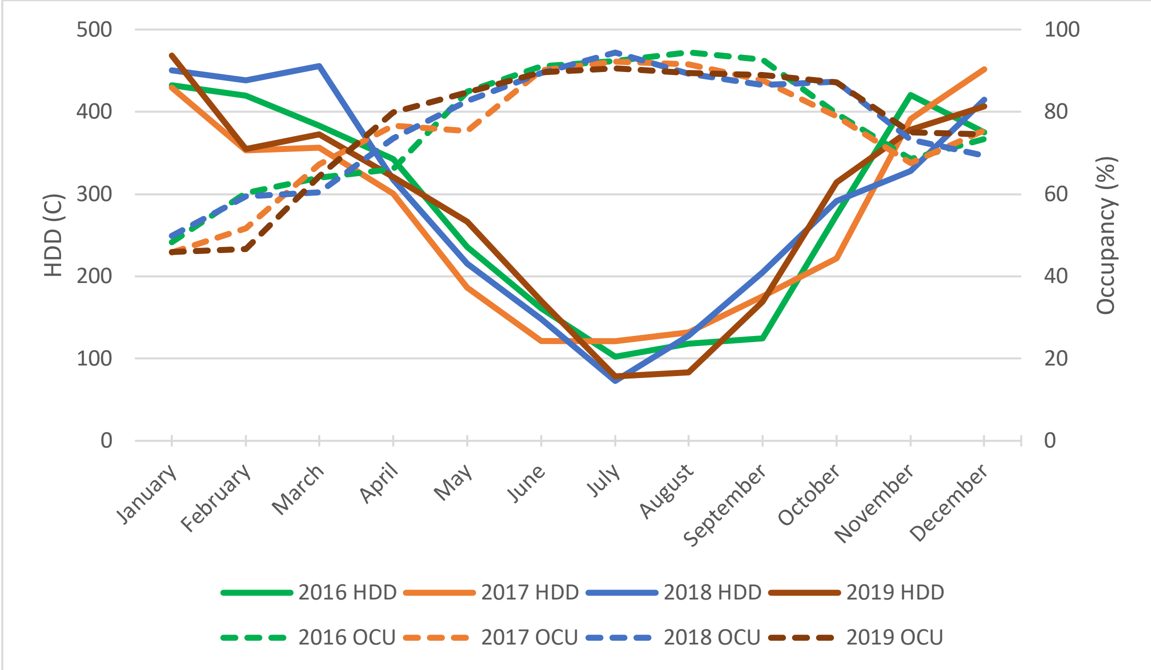


Figure 8.5 Monthly HDD and occupancy rates during the period 2016–2019

The two statistical indicators of MBE and CV(RMSE) – introduced in chapter 3 – are used as a means of comparison, Table 8.5. Based on the numbers calculated for MBE, for the most recent two years, the EPC calculation has underestimated the measured energy consumption. However, it should also be noted that the simulation result is very closely reflecting the hotel's energy consumption in 2019, which can also be recognised in Figure 8.4

Table 8.5 Statistical indicators for estimated data when compared with measured data

	2016	**2017**	**2018**	**2019**
MBE	8.92%	34.37%	-7.95%	-3.95%
CV(RMSE)	20.75%	35.87%	17.89%	6.71%

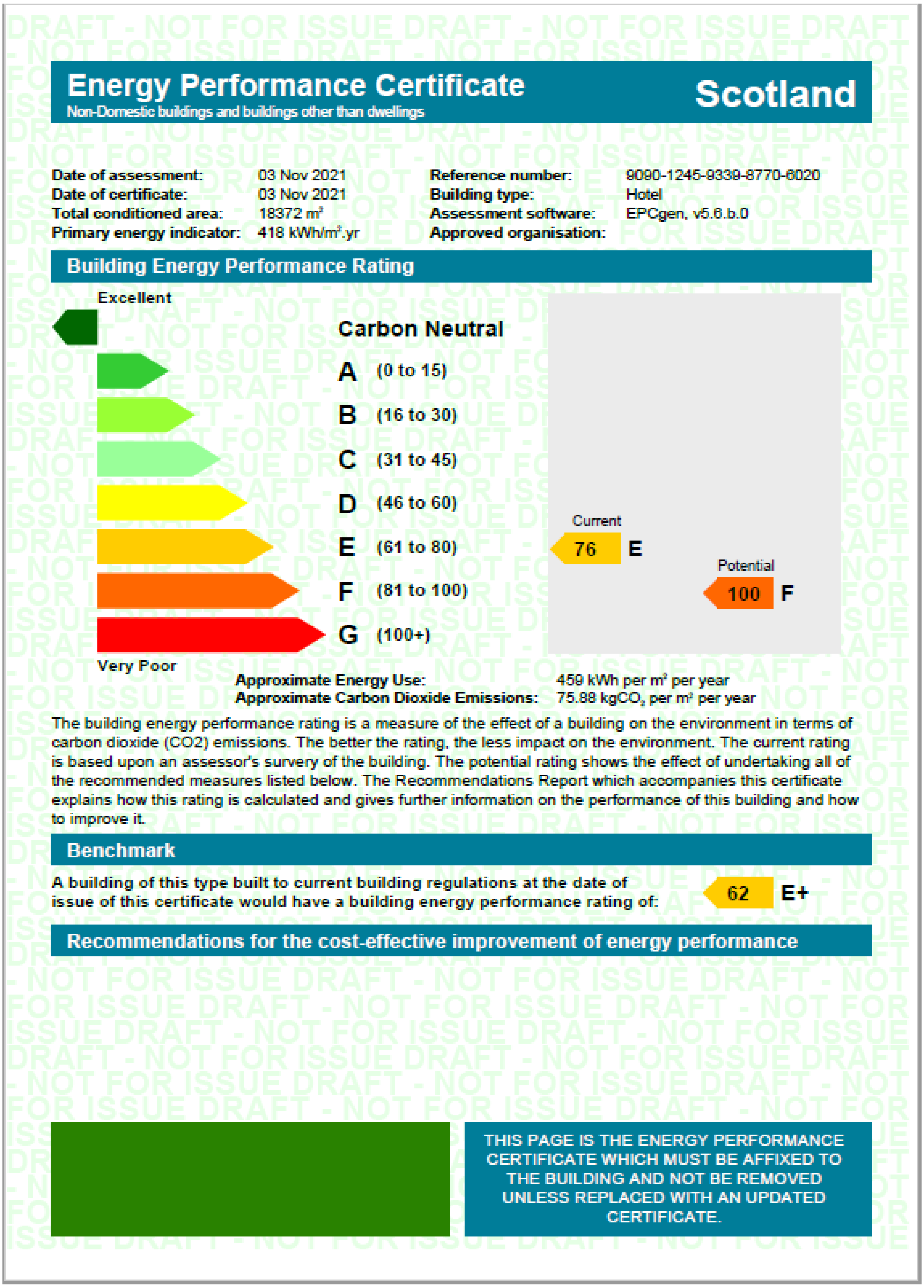
8.5.3 Hotel's rating in English EPC

As mentioned at the start of this chapter, due to the difference in methodology, the English and Scottish EPCs are not directly comparable. Especially as the English version tends to rate the building in a more favourable EPC band compared to when the same building is assessed by the Scottish scheme. This is exactly the case for this hotel. Figure 8.7 shows the hotel's EPC rating in each of these two frameworks. Despite a poor EPC rating in Scottish scheme – E (76) – the hotel receives an EPC rating of B (37) when assessed under the English version, which is by no means a “poor” rating. Despite this considerable difference in the rating, the CO_2 emission and the primary energy consumption calculated by either of the scheme are very close, as shown in the pictures. Similarly, the annual energy consumption calculated by each framework closely match the other one, 459 kWh/m^2 in Scottish scheme and 458.18 kWh/m^2 in English version.

Another point not to be missed is that both Scottish and English EPC show the benchmark; the rating of a similar building of this type built to current building regulations. The Scottish EPC illustrates that this theoretical building would have achieved an EPC rating of E$^+$(62), while the rating in the English version would have been B (32). This means that even when a building is built to the latest regulation and meets the minimum requirements defined in them for building services such as heating system’s efficiency, still, it won’t get a rating better than E in the Scottish scheme. This is a signal that improving the EPC rating of this building to bands better than E may not be easily achieved.

The question that may arise here is that why despite having a leaky fabric and being energy intensive, the hotel receives an EPC band B, signalling a good energy performance for the hotel? The answer lies in the mechanism behind incorporating a CHP system in EPC calculation. As explained in chapter 4 (see section 4.6.5.2) when a CHP is incorporated, the CO_2 emission that is saved by not using the electricity grid is deducted from the sum of CO_2 emission from heating, cooling, DHW, lighting and auxiliary end-uses. For example, here, the electricity generated by the CHP aka grid displaced electricity calculated in the English EPC amounts to 114.49 kWh/m^2, resulting in a sum of 59.42 kg CO_2/m^2 being removed from what is calculated as the sum of the end-uses’ emission. This is a noticeable deduction and puts the building in a good EPC band.

The fact that, due to its methodology, the Scottish EPC tends to place buildings in poorer energy bands can impose some consequences in terms of securing investments and/or financial aids from banks on the owners of commercial buildings and stakeholder in Scotland.



Energy Performance Certificate — **Scotland**

Non-Domestic buildings and buildings other than dwellings

Date of assessment:	03 Nov 2021	**Reference number:**	9090-1245-9339-8770-6020
Date of certificate:	03 Nov 2021	**Building type:**	Hotel
Total conditioned area:	18372 m²	**Assessment software:**	EPCgen, v5.6.b.0
Primary energy indicator:	418 kWh/m².yr	**Approved organisation:**	

Building Energy Performance Rating

Excellent

Carbon Neutral

A (0 to 15)

B (16 to 30)

C (31 to 45)

D (46 to 60)

E (61 to 80)

F (81 to 100)

G (100+)

Very Poor

Current 76 E

Potential 100 F

Approximate Energy Use: 459 kWh per m² per year

Approximate Carbon Dioxide Emissions: 75.88 $kgCO_2$ per m² per year

The building energy performance rating is a measure of the effect of a building on the environment in terms of carbon dioxide (CO2) emissions. The better the rating, the less impact on the environment. The current rating is based upon an assessor's survery of the building. The potential rating shows the effect of undertaking all of the recommended measures listed below. The Recommendations Report which accompanies this certificate explains how this rating is calculated and gives further information on the performance of this building and how to improve it.

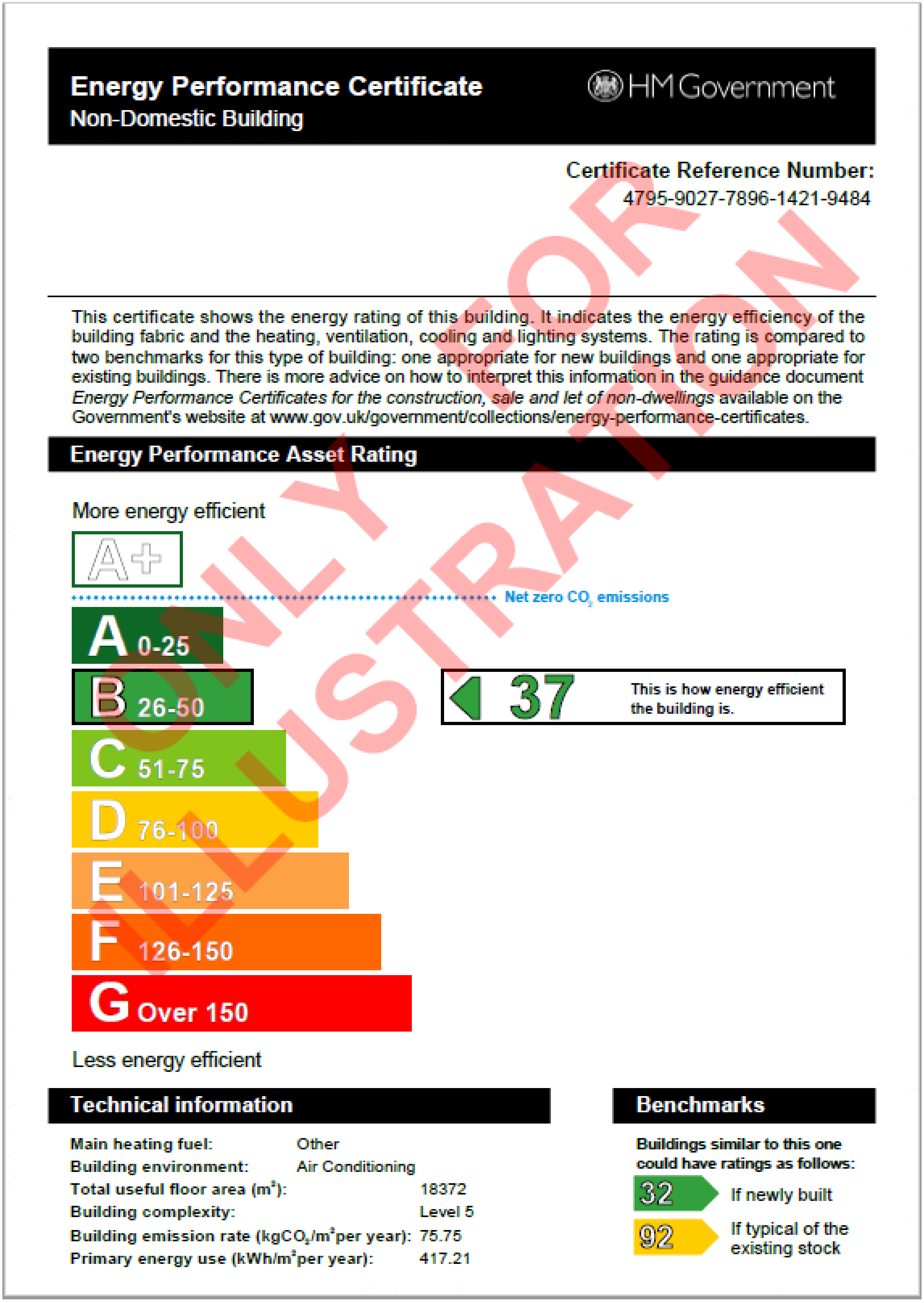
Benchmark

A building of this type built to current building regulations at the date of issue of this certificate would have a building energy performance rating of: 62 E+

Recommendations for the cost-effective improvement of energy performance

THIS PAGE IS THE ENERGY PERFORMANCE CERTIFICATE WHICH MUST BE AFFIXED TO THE BUILDING AND NOT BE REMOVED UNLESS REPLACED WITH AN UPDATED CERTIFICATE.

(a) Rating in the Scottish EPC



Energy Performance Certificate
Non-Domestic Building

HM Government

Certificate Reference Number:
4795-9027-7896-1421-9484

This certificate shows the energy rating of this building. It indicates the energy efficiency of the building fabric and the heating, ventilation, cooling and lighting systems. The rating is compared to two benchmarks for this type of building: one appropriate for new buildings and one appropriate for existing buildings. There is more advice on how to interpret this information in the guidance document *Energy Performance Certificates for the construction, sale and let of non-dwellings* available on the Government's website at www.gov.uk/government/collections/energy-performance-certificates.

Energy Performance Asset Rating

More energy efficient

A+

Net zero CO_2 emissions

A 0-25

B 26-50

C 51-75

D 76-100

E 101-125

F 126-150

G Over 150

Less energy efficient

37 This is how energy efficient the building is.

Technical information

Main heating fuel:	Other
Building environment:	Air Conditioning
Total useful floor area (m^2):	18372
Building complexity:	Level 5
Building emission rate ($kgCO_2/m^2$ per year):	75.75
Primary energy use (kWh/m^2 per year):	417.21

Benchmarks

Buildings similar to this one could have ratings as follows:

32 If newly built

92 If typical of the existing stock

(b) Rating in the English EPC

Figure 8.6 Comparing the hotel's rating in English and Scottish EPC

8.5.4 Retrofitted models

8.5.4.1 Improving thermal performance of windows

As mentioned earlier, the hotel's windows are mostly single layered. Given the climatic conditions, this can increase the heat loss from the building fabric considerably, contributing to high levels of heating demand. The upgrades are carried out by replacing the single-layered glazing with:

- Double-glazed unit consisting of two layers of 4 mm glazing with a Low-*E* coating and a 12 mm air-filled gap; retrofitted model 1 (RM1)
- Double-glazed unit consisting of two layers of 4 mm glazing with a Low-*E* coating and a 12 mm Argon-filled gap; retrofitted model 2 (RM2)
- Triple-glazed unit consisting of three layers of 4 mm glazing with two Low-*E* coatings and 12 mm Argon-filled gaps; retrofitted model 3 (RM3)

As expected, by upgrading the existing windows - except those on the basement level - the heating load of the building is reduced, Table 8.6. As elaborated in chapter 4 (see section 4.4.3.2), size fraction is the proportion of the "peak" load that will be met by the CHP system. Table 8.6 shows that the peak heat load is also reduced in all the retrofitted models. As the specification of the CHP system is kept unchanged in the retrofitted models, the same amount of heat output from CHP – i.e., 370 kW – would be able to meet more of the peak load, resulting in increased size fractions for the retrofitted models.

Table 8.6 Total and peak heating loads and size fractions for the models

Model	Heating load (kW)	Peak heat load (kW)	Heat output of the CHP (kW)	Size fraction
Baseline	874,095.09	660.72	370	0.56
RM1	629,539.63	545.82	370	0.68
RM2	605,977.47	533.74	370	0.69
RM3	579,065.51	511.79	370	0.72

The result of the EPC calculation is shown in Table 8.7. As it can be seen, upgrading the windows from single layered glazing can reduce the emission, however, changes to the EPC are only marginal, with the retrofitted models still remaining within band E. Furthermore, the primary energy consumption (PEC) is also reduced in all the models with upgraded windows, with the highest level of reductions occurring in the model with triple glazing. As can be seen, upgrading the windows from single layered to double-layered (RM1) results in 8%, 3% and 9% reduction in CO_2 emission, energy consumption and PEC respectively. However, further improvement in windows' thermal performance - RM2 and RM3 - would result in much smaller changes when compared to RM1, although reductions in PEC is still noticeable.

Table 8.7 The EPC results of the models with upgraded glazing elements

Model	EPC	CO_2 emission (kg/m²)	Annual energy consumption (kWh/m²)	PEC (kWh/m²)	CHP generated electricity (kWh/m²)
Baseline	E (76)	75.88	459.16	417.92	114.92
RM1	E^+(70)	69.53	444.18	380.61	124.87
RM2	E^+(69)	68.97	442.32	377.38	125.41
RM3	E^+(68)	67.89	441.89	370.86	128.46

As illustrated in Table 8.7, the amount of electricity generated by the CHP system compared to the baseline model is increased for the retrofitted models. The reason is explained in the following paragraph.

As shown in Table 8.6, the heating load of the hotel is reduced by upgrading the windows, resulting in smaller amount of energy consumption for heating end-use. Therefore, the CHP space heating consumption is reduced too, leaving more of its hourly capacity for providing DHW end-use. Given what was explained in chapter 4 on the impact of CHP system on space heating and hot water energy use, the DHW energy use increases, Figure 8.7. The combined effect of reduced space heating and increased hot water consumption results in an overall increase in the heat consumption. This means more heat needs to be produced. For providing more by-product heat to the building, the CHP needs to generate more electricity – the heat to power ratio remains 1.4. Therefore, the CHP-generated electricity is increased for the retrofitted models.

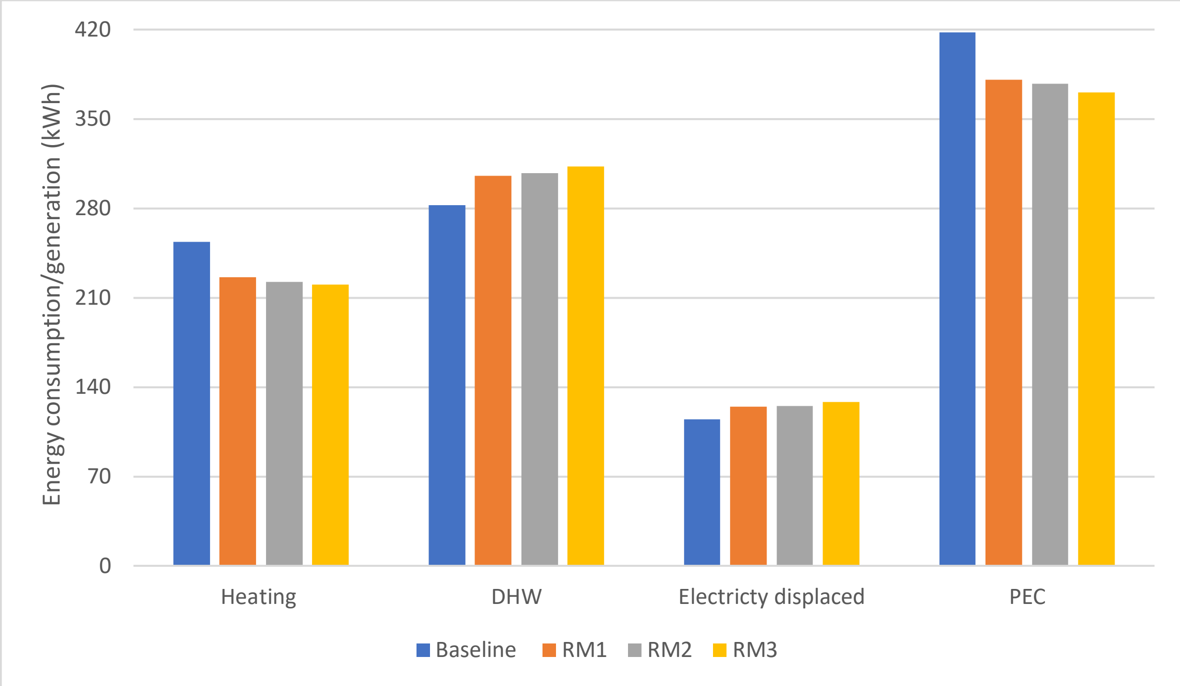


Figure 8.7 Changes in end-uses, displaced electricity, and primary energy consumption

8.5.4.2 Replacing the existing CHP system with heat pump

The next measure tested for improving the EPC rating is using heat pumps for space heating purpose. This measure is chosen with respect to the high share of this end-use (see Figure 8.4) and the established role of heat pumps in reducing the energy consumption and CO_2 emission. For the practicality and the fact that installing and using ground source heat pumps in an existing hotel of this size can be very challenging due to space needed, air source heat pumps (ASHPs) are suggested in this round of simulations.

Table 8.8 shows the results of simulation carried out with ASHPs installed for meeting part or all of the space heating demand:

- Retrofitted model 4 (RM4) shows the simulation results when the ASHP is serving only the guest rooms,
- Retrofitted model 5 (RM5) denotes the situation when ASHP is used for heating the guest rooms, pool and gym area
- Retrofitted model 6 (RM6) illustrates the results when ASHPs are used to heat all the zones in the hotel.

In all these simulations, the areas not covered by the ASHP, have their space heating demand met by gas-fired boilers. The heating efficiency of the ASHP was considered 300%.

Table 8.8 The EPC results of the models with ASHPs for space heating

Model	EPC	CO_2 emission (kg/m²)	Annual energy consumption (kWh/m²)	PEC (kWh/m²)
Baseline	E (76)	75.88	459.16	417.92
RM4	F (94)	93.73	340.53	538.65
RM5	F (93)	92.85	330.07	534.31
RM6	F+(90)	89.81	293.89	519.32

As shown in Table 8.8, replacing the existing CHP with ASHPs doesn't improve the EPC rating. In fact, it actually results in worsening the EPC rating, although the annual energy consumption is reduced. This is caused by two factors. First, in the absence of the CHP system and the electricity generated by it, no deduction from the sum of different end-uses' emission will take place. Second, the ASHP is using grid supplied electricity, which results in an increased amount of CO_2 emission due to its high carbon factor - 0.519 kg CO_2/kWh. With the Scottish EPC being a linear scale, any change to CO_2 emission is directly translated into a visible change to the EPC's numeric value. The combination of these two factors, results in increase of CO_2 emission up to 23% (RM4). The issue with unrealistically high carbon factors and its impact on the EPC rating was already discussed in preceding chapters for the English EPC. These findings make it clear that the Scottish EPC is also affected by this issue.

8.5.4.3 Using different cogeneration systems

In the previous section it was elaborated that one of the reasons contributing to a worsened EPC rating when replacing the CHP system with a heat pump is that in the absence of CHP system, no deduction from the hotel's CO_2 emission takes place. This suggests that inclusion of a CHP system has been very helpful in reducing the hotel's CO_2 emission hence EPC rating. To the extent that if the CHP was removed and the space heating and DHW demand of the hotel were to be met by gas-fired boilers, the EPC rating of the hotel would drop to band F (95) with 94.78 kg/m² of emission, 385.43 kWh/m² of annual energy consumption and 540.57 kWh/m² of primary energy consumption.

With that said, the next round of simulations is focused on CHP systems with different sizes and priorities and a less-discussed type of fuel. Therefore, in Table 8.9 the retrofitted models are:

- A system with smaller size i.e., kWe/248 kW CHP is used, prioritised on space heating; retrofitted model 7 (RM7). The capacity of the existing CHP is 260 kWe and 370 kW.
- The same CHP as the one in RM7 is used but the priority is set on DHW; retrofitted model 8 (RM8)
- A system with larger size i.e., 354 kWe/423 kW CHP is used, prioritised on space heating; retrofitted model 9 (RM9).
- The same CHP as the one in RM9 is used but the priority is set on DHW; retrofitted model 10 (RM10)
- A CHP system with the specification of 210 kWe/222 kW, using biogas as fuel, instead of natural gas. The CHP is prioritised on space heating; retrofitted model 11 (RM11).
- The same CHP as the one in RM10 is used but the priority is set on DHW; retrofitted model 12 (RM12)

Table 8.9 The EPC results of the models with different CHP systems

Model	EPC	CO_2 emission (kg/m^2)	Annual energy consumption (kWh/m^2)	PEC (kWh/m^2)	CHP generated electricity (kWh/m^2)
Baseline	E (76)	75.88	459.16	417.92	114.92
RM7	E (80)	80.27	444.68	446.18	90.1
RM8	E (78)	78.08	449.19	432.36	100.54
RM9	E^+(67)	66.77	472.53	360.96	154.53
RM10	E^+(64)	63.63	479.02	341.15	169.51
RM11	D (53)	52.42	443	415.97	90.31
RM12	D^+(46)	46.38	447.86	396.19	102.23

The reason for trying biogas-fuelled CHP system is that biogas is known as a renewable and alternative fuel that can assist to reduce the consumption of fossil fuel. A CHP using biogas usually relies on methane gas. In all these models, the overall efficiency of the CHP system is kept at 80%.

As illustrated in Table 8.9, a smaller CHP system would not help the EPC rating, making it even slightly worse. Choosing a larger CHP system can improve the EPC rating, especially when the system is prioritised on DHW. This better performance can be explained as follows: it is generally accepted that in order to derive benefit from CHP, it should be always running. Setting the priority to DHW will guarantee that (EDSL TAS, 2013). As the Scottish EPC follows the NCM standard profiles, the assumptions for DHW demand being constant at every hour of the year is applied here. In order for the CHP to produce enough by-product heat to meet this constant and overestimated - see chapter 6 - demand, the generating of electricity is increased to 169.51 kWh/m^2. The increased electricity generated by the CHP means larger removal from the sum of all end-uses' emission, hence a better EPC rating.

Looking at the results for RM11 and RM12 representing biogas-fuelled CHP systems, remarkable reductions in the hotel's emission rate are achieved, improving the EPC rating to band D, which couldn't be achieved through any of the previous measures. This considerable reduction in CO_2 emission is caused by much smaller carbon factor for biogas, i.e., 0.098 kg/kWh as opposed to that of natural gas which is 0.216 kg/kWh. The reason for the carbon factor of biogas being much smaller is that biogas is mainly produced through an anaerobic digestion process or fermentation of biodegradable materials such as biomass, manure or sewage and even municipal waste. The breaking down of the organic waste is carried out by bacteria in an oxygen-free environment (Farhad, Hamdullahpur and Yoo, 2010). The impact of the carbon factor in determining the EPC rating is evident when RM11 is compared with RM7 or RM12 is compared with RM8. While the CHPs have almost similar sizing and the values for annual energy consumption and generated electricity almost match in corresponding models, the values for CO_2 emission differ massively, as do EPC ratings, all down to the carbon factor used in RM11 and RM12. As briefly mentioned in 8.5.3, a building similar to this case, compliant with the current building regulations would have an EPC rating of E$^+$(62). In RM11 and RM12, through biogas-fuelled CHP, the hotel's emission proved better than this base case scenario.

As shown, in terms of reducing the emission and improving the EPC rating, the biogas-fuelled CHP can be very beneficial, however, in terms of practicality, it needs consistent supply of fuel for the system to run smoothly. Furthermore, for the system to run properly, the fuel should be of high quality and with biogas, there is usually a risk of contamination at the process stage, due to various reasons from excessive water in the tanks storing the organic waste and cleaning agents creating unwanted chemicals, etc. (HELEC, 2021).

8.6 Summary and conclusion

In this chapter, a hotel under the Scottish EPC scheme was studied. After going through the similarities and differences between the English and Scottish EPC, different measures for improving the EPC rating of a hotel falling within the Scottish framework were applied. These measures were chosen based on the findings from chapter 7 and the breakdown of the hotel's estimated energy consumption. They were focused on reducing the emissions from space heating and DHW, the two end-uses with highest share in annual energy consumption estimated by the EPC calculation.

Improving thermal performance of the windows by upgrading them from single-layered glazing to double and triple glazing reduced CO_2 emissions, but this reduction was not big enough to change the EPC band. Despite having a notable contribution to reducing the heating demand, the impact on the EPC rating is minimal.

With the finding that replacing the existing CHP system with heat pumps would worsen the EPC rating, the efforts were aimed at CHP related measures. Regardless of the type and size of the CHP, prioritising the CHP on DHW proved a useful tool for improving the EPC rating. As discussed, this is due to the assumptions defined by the NCM activity database ensuring that there is always a constant demand for DHW, requiring the CHP to be constantly running so that enough heat is yielded during the electricity generation process.

The carbon factors proved impactful on Scottish EPC, too. By replacing the CHP system with heat pumps, the benefit of deducting the CHP-generated electricity and its equivalent emission from the hotel's end-uses is taken away. Furthermore, the space heating energy use by the heat pump is translated into CO_2 emission with higher carbon factor. The unrealistically high carbon factor for grid supplied electricity is the main culprit here. Furthermore, when the

CHP system was changed from natural gas to biogas, a considerable reduction in CO_2 emission was achieved, improving the EPC rating to band D. Despite the promising results, there are doubts about consistent supply of high-quality biogas for the system to operate smoothly.

The main conclusions from this chapter can be highlighted below:

- Due to the differences in methodology, the hotel examined here was rated very differently in Scottish EPC compared to the English EPC.
- Because of the methodology used in defining the Scottish EPC bands, even if the hotel was built to the current regulation, it would still receive an EPC band of E and not any better.
- As the Scottish EPC is based on a linear scale of CO_2 emission, the impact of carbon factors becomes even more noticeable. The unrealistically high carbon factor for grid-supplied electricity at the time of writing - November 2021 - causes unhelpful results, such as finding that heat pumps are not useful in reducing the CO_2 emission of this hotel. This is contrary to the established role of heat pumps in reducing CO_2 emissions through their high efficiency.
- Following the previous point about the Scottish EPC being based on a linear scale of CO_2 emission, using biogas with a carbon factor lower than that of natural gas, proved very helpful in improving the EPC rating to band D.
- As the NCM guidelines are applied here too, the need for DHW is constant at all hours, therefore, prioritizing the CHP system on DHW ensures higher level of electricity generation, hence better EPC rating.

Chapter 9 Summary and conclusion

9.1 Summary of the work

This study was motivated by the inauguration of Minimum Energy Efficiency Standard (MEES) which relates to the EPC rating of commercial buildings. The focus of the study was on hotel buildings. Different aspects of non-domestic EPCs - both English and Scottish versions - and the NCM standard assumptions were studied through four different cases in the UK hotel buildings sector. These aspects ranged from the means of improving an EPC, sources of overestimation and underestimation to the difference between saving energy consumption and reducing CO_2 emissions, etc. In order to investigate these matters, computational fluid dynamic software tool EDSL TAS was used. This software is approved and accredited by the UK Government for conducting non-domestic EPC assessment.

The research questions outlined in chapter 1 have all been addressed through different chapters. Below is the brief summary of the main findings with regards to the research questions.

1. **With regards to the expected rise in temperature and the goal of attending to guests' comfort, what is the impact of adding cooling systems on a hotel's EPC rating?**

Cooling is one of the five fixed services for which the energy consumption and CO_2 emissions are calculated to determine an EPC rating. As such, in order to calculate the impact of adding cooling systems, the extent of the resultant increase in the hotel's electricity consumption and its knock-on impact on CO_2 emissions should be assessed. The magnitude of the increase depends on the cooling load and the efficiency of the system.

In order to calculate the cooling load for any zone, all the heat transfer mechanisms affecting the zone are considered. By determining the cooling load, the rate at which heat should be removed from a zone to maintain its indoor environment at a required condition becomes clear. For the sake of EPC calculation, this required condition is assigned by NCM Activity database, based on which, the cooling set point is set to 25°C for guest rooms. This means that the cooling system in a guest room only starts to work when the indoor temperature exceeds 25°C and continues working to maintain this temperature. One of the important factors affecting the indoor temperature is the outdoor weather. In the UK, for the purpose of compliance modelling including EPC assessment, Test Reference Year (TRY) weather files should be used. TRY files are composed of 12 separate months of data each selected to represent the most average month from period 1984–2013. Therefore, the TRY are normalised, and they do not reflect the expected rise in temperature.

The case that this calculation is based on was described in chapter 5. With the London TRY weather file and set point of 25°C, the cooling load of the 180 guest rooms were rather small. Therefore, by installing cooling system with a minimum energy efficacy rate of 2.6, the extra electricity consumption and CO_2 emission were only enough to increase the asset rating from 53 to 54, with the EPC band remaining unchanged.

While each case should be assessed individually, with the existing assumptions from NCM Activity database and the TRY weather files representing normalised temperatures rather than warmer summers, chances are high that adding cooling systems does not adversely affect the EPC rating of a hotel.

See chapter 5 for full details.

2. Is there any source of controversy in the existing framework of the EPC for hotels?

The non-domestic EPC evaluates the performance of a building based on its annual CO_2 emission. For the purpose of converting energy consumption to CO_2 emissions, carbon factors are used. The carbon factors used in EPC calculation are assigned and issued by NCM. Currently, the carbon factors for grid supplied electricity and natural gas are 0.519 and 0.216 kg/kWh, respectively, showing a high carbon factor for grid supplied electricity, despite the grid becoming greener. This unrealistically high carbon factor for electricity can lead to controversial results. For instance, if in a hotel, space heating and DHW are provided by gas-fired boilers with efficiency of 91% and then these boilers are replaced with electric heaters with 100% efficiency, despite achieving a reduction in annual energy consumption, there is a considerable increase in the emission rate resulting in an obvious worsening of the EPC rating.

Further cases on a smaller scale, are discussed in chapter 7, where it's found that despite a reduction in annual energy consumption, there has been an increase in the emission rate followed by an increase in the EPC rating.

Another source of controversy was spotted between the English and Scottish EPCs. The NCM Activity database that applies to the English EPC is also applicable to the Scottish version, but as shown in chapter 8, due to different methodology, while one hotel can be rated as energy efficient in English EPC, it can receive a considerably poorer rating in the Scottish version. Although this difference in methodology means the ratings in the two frameworks are not comparable, issues such as difficulty securing financial help and loans may still arise as a result of this.

See chapters 4, 7 and 8 for full details.

3. Is there any source of uncertainty in the existing framework of the EPC for hotels?

Based on the simulation results carried out for four different hotels within the UK, comparisons with measured data and information from the literature, it is concluded that the EPC assessment for hotels underestimates the cooling energy consumption and overestimates the DHW energy consumption. While it is possible that the combined effect of these two uncertainties balance each other's impact to some level (in terms of the impact on estimated annual energy consumption), the extent of this combined impact is not clear.

As the main reason behind both of these uncertainties are the NCM Activity database assumptions which they are mandatory to follow, the impact of these uncertainties is spread to all the hotels in the UK applying for an EPC.

Another source of uncertainty within the existing framework is that there is no guideline on how to validate the EPC results. As the EPC assessment has to use pre-defined values for some parameters such as occupancy hours, temperature set points, etc. it cannot be validated against the measured data from the actual building. Furthermore, there is a clear risk of receiving different EPC results when different assessors evaluate the same building. The risk especially increases if different tools are used for assessment.

See chapters 5 and 6 for full details.

4. Within the current framework of the non-domestic EPCs, what are the key factors in determining a hotel's EPC rating?

Looking at the breakdown of energy consumption estimated for the four hotels studied in this work (see chapter 6 and 8 for the graphs), it is observed that the highest share belongs to DHW usage. In the EPC calculation, the energy demand for DHW is calculated as the energy required to increase the temperature of the water from 10°C to 60°C and the demand for hot water. The hot water demand for each activity is a figure expressed in l/m^2 per day and assigned by the NCM Activity database. Then based on the system's efficiency (including the distribution losses), the energy consumption for meeting this demand is calculated.

Based on the sensitivity analysis carried out in chapter 7 and the fact that parameters determining the hot water demand for any given hotel are fixed (i.e., the value assigned by the NCM, and the area covered by the respective activity), the system's efficiency has the highest impact on the EPC rating. As fully explained, if the same system also provides space heating, then its efficiency has an even more significant impact on the EPC rating. However, if the space heating is provided through a separate system, then the heating system's efficiency is the parameter with the second highest impact on the EPC rating.

This means that if there is the need to improve the EPC band (rather than just the asset rating) in order to comply with MEES, increasing the efficiency of the DHW system and/or the heating system can be very helpful. By comparison, the impact derived from improving the lighting system or the efficiency of the cooling system is much less significant. On a similar note, improving the building fabric's thermal performance through increasing the thermal insulation thickness is of negligible impact, if any at all.

See chapter 7 for full details

5. Can MEES effectively reduce the CO_2 emissions in the UK hotel buildings?

MEES and similar policies are all designed and executed with the goal of reducing CO_2 emissions from the building sector. In order to predict the impact from MEES on the hotel sector's CO_2 emissions, this work has taken a critical look at its main player, non-domestic EPC. The EPC in the UK has definitely contributed to demonstrating the energy performance of commercial sector for policy makers and the public. However, the uncertainties involved in NCM Activity database assumptions for hotels such as overestimation of the DHW energy use means that its position among stakeholders could be at risk. Furthermore, the shortcomings involved in the existing framework may result in unrealistic expectations of how much energy and CO_2 emission savings can be achieved upon carrying out a specific energy retrofitting measure.

For instance, if a hotel with EPC band F (non-complying with MEES) undergoes some measures to improve the DHW system's efficiency, it might achieve a rating of band E. This is despite the fact that the actual share of DHW in actual energy consumption/CO_2 emission is much less than EPC's calculation credits it for, meaning the saving in CO_2 emission attributed to the change may not be anywhere near as significant. On this basis, it could be claimed that beyond the theoretical values, the actual contribution of MEES to reducing real emissions may be considerably less than the theoretical figures would suggest.

In another example, in a hotel already complying with MEES requirement, cooling systems – either local or central systems – are added to guest rooms with only marginal impact on the EPC rating. However, in reality, the increase in energy consumption and CO_2 emission resulting from the newly added cooling systems may be much more than the small amount estimated by the EPC caused by unrealistic assumptions of occupant behaviour.

The review of existing literature revealed that non-domestic EPC has not received enough attention over the years since its inauguration and that this is not limited to the UK. In all the countries which followed the EPBD requirements and devised methodologies for showing the energy performance of their building sector, the non-domestic EPC has always been under-researched.

The research answers summarised in preceding paragraphs offer original research into the effectiveness of the MEES requirements in the context of hotels. The bottom line is that unless the uncertainties and shortcomings within the existing framework of EPC for hotels are rectified, contributions from MEES - in the hotel sector - may remain only on paper. Furthermore, the reliability of the EPC within the sector may be called into question, leading to portraying it as a financial and executive burden rather than a justifiable and beneficial piece of legislation.

9.2 Limitation of the work

This thesis found some significant issues with non-domestic EPCs stemming from NCM Activity database profiles for hotels. These issues can compromise the reliability of the EPC and effectiveness of the MEES in the hotel sector. Despite the findings of the work, the author believes that this work should be considered as the first step into investigating the non-domestic EPC with a view to improving the quality of the scheme.

The main limitation of this thesis is associated with the restrictions of building modelling and energy simulation tools, even within the scope of compliance modelling. While all steps were taken to ensure precise modelling and simulations, the currently available software tools all come with limitations intrinsic to them.

Another limitation of this thesis is the number of cases studies. While the hotels used in this study were varied and the findings are related to NCM standard profiles and not a specific case, it is clear that a larger sample size would have been beneficial. However, due to the unexpected nature of events during 2020 and early 2021 and the huge impact on the hospitality industry - e.g., full closure of hotels for several months followed by extremely low occupancy rates in the next months - it was not possible to include more cases within the course of this PhD.

9.3 Future work

MEES requirement is applied to a range of non-domestic buildings, however, hotels were studied in this work. The process of generating EPC for the other non-domestic buildings, e.g., offices is more or less the same; the NCM profiles are used according to the building type alongside the information about the building's fixed services and its fabric. Future works can look into the NCM profiles for other building types and apply a methodology similar to the one used in this thesis to investigate the reliability of the ECP and effectiveness of MEES in that sector.

Furthermore, given the discussions about the limitations of compliance modelling, especially the fact that it does not reflect buildings' operational performance, a future work can look into the pros and cons of using measured data for illustrating the energy performance of the hotel sector. The study could look at the possibility of splitting the mandatory reporting of the energy performance for hotels into two different levels with one being compliance modelling when a new hotel is constructed and the other one being performance modelling. That's to say reporting the energy performance of the building based on how it is actually operated and the need to update it within a specific time.

9.4 Research findings in a list

The research questions were all answered and a brief summary of them was provided in Section 9.1. Below is the list of research findings for a quick reference:

- Tendency towards preferring natural gas due to unrealistic carbon factors: The existing carbon factors for fuels are not realistic. There is an unrealistically high carbon factor for grid supplied electricity as opposed to a much smaller value for natural gas.
- DHW usage is overestimated for hotels. This can result in unrealistic expectations from energy retrofitting measures aimed at this end-use.
- Cooling energy use is underestimated for hotels. This can result in failing to recognise the environmental impact of adding cooling system.
- Significant changes to EPC rating are mostly possible through increasing the efficiency of DHW and/or heating system.
- Increasing the efficiency of cooling system is not followed by a considerable improvement in the EPC, while if this measure is taken, there might be considerable savings in the actual energy consumption.

- It is almost impossible to improve the EPC by increasing the thermal insulation (i.e., reducing the U-value) of building fabric's solid elements.
- Despite the risk of getting different results through repeated calculations, there is no approved means of checking the reliability of EPCs.
- English EPC rates a building in a better band than what the Scottish EPC does to the same building.

References

3M (2019) *3M Thinsulate Window Films Climate Control Series*. Available at: https://www.3m.com/3M/en_US/company-us/all-3m-products/~/3M-Thinsulate-Window-Film-Climate-Control-Series-for-Residential/?N=5002385+3292123816&preselect=3293786499&rt=rud (Accessed: 20 March 2019).

Abela, A. *et al.* (2016) 'An investigation of the appropriateness of current methodologies for energy certification of Mediterranean housing', *Energy and Buildings*, 130, pp. 210–218. doi: 10.1016/J.ENBUILD.2016.07.056.

Aburas, M. *et al.* (2019) 'Thermochromic smart window technologies for building application: A review', *Applied Energy*, 255, p. 113522. doi: 10.1016/J.APENERGY.2019.113522.

Actione Energy (2004) *Good Practice Guide 388: Combined heat and power for buildings*. Available at: http://www.cwp-ltd.com/wp-content/uploads/2012/03/UKGoodPracticeGuide.pdf.

Ahern, C. and Norton, B. (2020) 'Energy Performance Certification: Misassessment due to assuming default heat losses', *Energy and Buildings*, 224, p. 110229. doi: 10.1016/j.enbuild.2020.110229.

Ahmad, M. and Culp, C. H. (2006) 'Uncalibrated Building Energy Simulation Modeling Results', *HVAC&R Research*, 12(4), pp. 1141–1155. doi: 10.1080/10789669.2006.10391455.

Al-Homoud, M. S. (2001) 'Computer-aided building energy analysis techniques', *Building and Environment*, 36(4), pp. 421–433. doi: https://doi.org/10.1016/S0360-1323(00)00026-3.

Alarcon-Rodriguez, A., Ault, G. and Galloway, S. (2010) 'Multi-objective planning of distributed energy resources: A review of the state-of-the-art', *Renewable and Sustainable Energy Reviews*, 14(5), pp. 1353–1366. doi: https://doi.org/10.1016/j.rser.2010.01.006.

Allouhi, A. *et al.* (2015) 'Energy consumption and efficiency in buildings: Current status and future trends', *Journal of Cleaner Production*, 109, pp. 118–130. doi: 10.1016/j.jclepro.2015.05.139.

Amecke, H. (2012) 'The impact of energy performance certificates: A survey of German home owners', *Energy Policy*, 46, pp. 4–14. doi: 10.1016/J.ENPOL.2012.01.064.

Annunziata, E., Frey, M. and Rizzi, F. (2013) 'Towards nearly zero-energy buildings: The state-of-art of national regulations in Europe', *Energy*, 57, pp. 125–133. doi: https://doi.org/10.1016/j.energy.2012.11.049.

Arcipowska, A. *et al.* (2014) *Energy Performance Certificates Across the EU. A mapping of National Approaches*. Buildings Performance Institute Europe (BPIE). Available at: http://bpie.eu/publication/energy-performance-certificates-across-the-eu/.

Arkesteijn, K. and Dijk, D. Van (2010) *Energy performance certification for new and existing buildings. Differences in approach, the role of choice in CEN standards application.* Available at: http://www.buildup.eu/sites/default/files/content/P156_EN_CENSE_New_and_existing_buildings.pdf.

ASHRAE (2004) 'The systems and equipment', in *ASHRAE Hanbook*. Atlanta.

ASHRAE (2013) 'Nonresidential heating and cooling load calculations', in *ASHRAE Handbook of Fundamentals*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Atanasiu, B. and Constantinescu, T. (2011) 'A comparative analysis of the energy performance certificates schemes within the European Union: Implementing options and policy recommendations', in *ECEEE Industrial Summer Study Proceedings*, p. 10. Available at: https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2011/2-current-energy-efficiency-policies-on-stage-and-backstage/a-comparative-analysis-of-the-energy-performance-certificates-schemes-within-the-european-union-implementing-options.

Augenbroe, G. (2002) ‘Trends in building simulation’, *Building and Environment*, 37(8), pp. 891–902. doi: https://doi.org/10.1016/S0360-1323(02)00041-0.

Babaei, T. *et al.* (2015) ‘A study and a directory of energy consumption data sets of buildings’, *Energy and Buildings*, 94, pp. 91–99. doi: https://doi.org/10.1016/j.enbuild.2015.02.043.

Backhaus, J., Tigchelaar, C. and de Best-Waldhober, M. (2011) *Key Findings and Policy Recommendations to Improve Effectiveness of Energy Performance of Building Directive*. Netherlands.

Bahadori-Jahromi, A. *et al.* (2017) ‘Impact of window films on the overall energy consumption of existing UK hotel buildings’, *Sustainability (Switzerland)*, 9(5), pp. 1–23. doi: 10.3390/su9050731.

Balaras, C. A. *et al.* (2016) ‘Empirical assessment of calculated and actual heating energy use in Hellenic residential buildings’, *Applied Energy*, 164, pp. 115–132. doi: 10.1016/J.APENERGY.2015.11.027.

Barker, T. *et al.* (2007) *Mitigation from a cross-sectoral perspectiv*. Cambridge: Cambridge University Press.

Bartiaux, F. *et al.* (2011) ‘Knowledge on Climate Change and Energy Saving Renovations by Apartment Owners in Bulgaria and Latvia. A Qualitative Study’, *International Review of Social Research*, 1(3), pp. 133–154. doi: 10.1515/irsr-2011-0024.

BBP (2019) *DESIGN FOR PERFORMANCE A new approach to delivering energy efficient offices in the UK*. London. Available at: https://www.betterbuildingspartnership.co.uk/our-priorities/measuring-reporting/design-performance.

BEIS (2013) *Combined heat and power, Department for Business, Energy & Industrial Strategy*. Available at: https://www.gov.uk/guidance/combined-heat-and-power (Accessed: 21 October 2021).

BEIS (2014) *Combined Heat and Power Quality Assurance Program. Certification for Good Quality CHP and CHPQA financial incentives., Department for Business, Energy & Industrial Strategy*. Available at: https://www.gov.uk/guidance/combined-heat-power-quality-assurance-programme (Accessed: 21 October 2021).

BEIS (2017) *The non-domestic Private Rented Property minimum standard – landlord guidance*. Available at: https://www.gov.uk/government/publications/the-non-domestic-private-rented-property-minimum-standard-landlord-guidance.

Bianco, V. *et al.* (2017) ‘Modeling energy consumption and efficiency measures in the Italian hotel sector’, *Energy and Buildings*, 149, pp. 329–338. doi: 10.1016/j.enbuild.2017.05.077.

BizEE Software (2021) *Degree Days Calculated Accurately for Locations Worldwide*. Available at: https://www.degreedays.net/ (Accessed: 2 July 2021).

Bodach, S., Lang, W. and Auer, T. (2016) ‘Design guidelines for energy-efficient hotels in Nepal’, *International Journal of Sustainable Built Environment*, 5(2), pp. 411–434. doi: 10.1016/j.ijsbe.2016.05.008.

Bogdan, R. and Biklen, S. K. (2003) *Qualitative Research for Education: An Introduction to Theories and Methods, 4th Edition*. Pearson.

Bohdanowicz, P. and Martinac, I. (2007) ‘Determinants and benchmarking of resource consumption in hotels-Case study of Hilton International and Scandic in Europe’, *Energy and Buildings*, 39(1), pp. 82–95. doi: 10.1016/j.enbuild.2006.05.005.

Bonde, M. and Song, H. (2013) ‘Is energy performance capitalized in office building appraisals?’, *Property Management*. Edited by S. Sayce, 31(3), pp. 200–215. doi: 10.1108/02637471311321450.

Bordass, B. *et al.* (2001) ‘Assessing building performance in use 3: energy performance of the Probe buildings’, *Building Research & Information*, 29(2), pp. 114–128. doi: 10.1080/09613210010008036.

Bordass, B., Cohen, R. and Field, J. (2004) ‘Energy performance of non-domestic buildings -

Closing the credibility gap', in *International conference on improving energy efficiency in commercail buildings*. Frankfurt, Germany.

Borgstein, E. H., Lamberts, R. and Hensen, J. L. M. (2016) 'Evaluating energy performance in non-domestic buildings: A review', *Energy and Buildings*, 128, pp. 734–755. doi: 10.1016/J.ENBUILD.2016.07.018.

Borrego, M., Douglas, E. P. and Amelink, C. T. (2009) 'Quantitative , Qualitative , and Mixed Research Methods in Engineering Education', *Journal of Engineering Education*, (January), pp. 53–66.

Bossmann, T., Eichhammer, W. and Elsland, R. (2012) 'Policy report. Contribution of energy efficiency measures to climate protection within the European Union until 2050.', *Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and Fraunhofer Institute for Systems and Innovation Research ISI*.

BPIE (2011) *Europe's buildings under the microscope: a country-by-country review of the energy performance of buildings, Buildings Performance Institute Europe (BPIE)*. Buildings Performance Institute Europe (BPIE). doi: ISBN: 9789491143014.

BRE (2006) 'Energy Pefromance of Building Directive', *Building Research Establishment*, p. 5. doi: 10.1680/cien.2010.163.2.53.

BRE (2019a) 'Briefing Note - Derivation and use of Primary Energy factors in SAP'. Building Research Establishment. Available at: https://www.bregroup.com/wp-content/uploads/2019/10/Briefing-note-on-derivation-of-PE-factors-V1.3-01-10-2019.pdf.

BRE (2019b) *Post-Occupancy Evaluation (POE), Building Research Establishment*. Available at: https://www.bre.co.uk/page.jsp?id=1793 (Accessed: 4 December 2020).

BRECSU (1993) *Energy Efficiency in Hotels - A Guide for Owners and Managers*. Available at: https://www.cibse.org/getmedia/142d96fa-7e76-4ec5-b305-1da2a7469819/ECG36-Energy-Efficiency-in-Hotels-A-Guide-for-Owners-and-Managers-1993,-rep-1997.pdf.aspx.

Bressand, F. *et al.* (2007) *Curbing global energy-demand growth: The energy productivity opportunity*. San Francisco. Available at: https://www.mckinsey.com/business-functions/sustainability/our-insights/curbing-global-energy-demand-growth.

Brøgger, M. and Wittchen, K. B. (2018) 'Estimating the energy-saving potential in national building stocks – A methodology review', *Renewable and Sustainable Energy Reviews*, 82(July 2017), pp. 1489–1496. doi: 10.1016/j.rser.2017.05.239.

Burman, E., Mumovic, D. and Kimpian, J. (2014) 'Towards measurement and verification of energy performance under the framework of the European directive for energy performance of buildings', *Energy*, 77, pp. 153–163. doi: 10.1016/j.energy.2014.05.102.

Buso, T. *et al.* (2017) 'Of comfort and cost : Examining indoor comfort conditions and guests ' valuations in Italian hotel rooms', *Energy Research and Social Science*, 32, pp. 94–111. doi: 10.1016/j.erss.2017.01.006.

Buso, T., Becchio, C. and Corgnati, S. P. (2017) 'NZEB, cost- and comfort-optimal retrofit solutions for an Italian Reference Hotel', *Energy Procedia*, 140, pp. 217–230. doi: 10.1016/j.egypro.2017.11.137.

Butzbaugh, J. B. *et al.* (2018) *Understanding the U.S. Commercial Building Stock: Building Envelope and HVAC Systems Characteristics Using 2012 CBECS Data Analysis*. Richland, WA (United States).

Cabello Eras, J. J. *et al.* (2016) 'Tools to improve forecasting and control of the electricity consumption in hotels', *Journal of Cleaner Production*, 137, pp. 803–812. doi: 10.1016/j.jclepro.2016.07.192.

Calama-González, C. M. *et al.* (2021) 'Bayesian calibration of building energy models for uncertainty analysis through test cells monitoring', *Applied Energy*, 282, p. 116118. doi: https://doi.org/10.1016/j.apenergy.2020.116118.

Capehart, B. L. (2016) *Distributed Energy Resources (DER), Whole Building Design guide (WBDG)*. Available at: https://www.wbdg.org/resources/distributed-energy-resources-der (Accessed: 19 October 2021).

Carbon Trust (2011) *Closing the gap. lessons learned on realising the potential of low carbon building design*. London.

Carbon Trust (2018) *Hospitality: Saving energy without compromising comfort*. London.

Carbon Trust (2020) *Energy benchmark tool*. Available at: https://www.carbontrust.com/resources/energy-benchmark-tool (Accessed: 23 September 2020).

Cardona, E. and Culotta, S. (2001) *CHOSE - energy saving by combined heat, cooling and power plants in the hotel sector*. Stockholm.

Cardona, E., Piacentino, A. and Cardona, F. (2006) 'Matching economical, energetic and environmental benefits: An analysis for hybrid CHCP-heat pump systems', *Energy Conversion and Management*, 47(20), pp. 3530–3542. doi: 10.1016/j.enconman.2006.02.027.

Cayre, E. *et al.* (2011) 'There are people in the house ! how the results of purely technical analysis of residential energy consumption are misleading for energy policies', in *ECEEE 2011 Summer Study. ENERGY EFFICIENCY FIRST: THE FOUNDATION OF A LOW-CARBON SOCIETY*. Belambra Presquile de Giens, France, pp. 1675–1683.

Chan, W. W. *et al.* (2013) 'Hotel heat pump hot water systems: impact assessment and analytic hierarchy process', *International Journal of Contemporary Hospitality Management*, 25(3), pp. 428–446. doi: 10.1108/09596111311311053.

Charalambides, A. G. *et al.* (2019) 'The impact of Energy Performance Certificates on building deep energy renovation targets', *International Journal of Sustainable Energy*, 38(1), pp. 1–12. doi: 10.1080/14786451.2018.1448399.

Charnes, A., Cooper, W. W. and Rhodes, E. (1978) 'Measuring the efficiency of decision making units', *European journal of operational research*, 2(6), pp. 429–444.

Chen, B., Ji, Y. and Xu, P. (2012) 'Impact of Window Shading Devices on Energy Performance of Prototypical Buildings', *Eps*, pp. 1–8. Available at: https://www.ibpsa.org/proceedings/asim2012/0148.pdf.

Chilisa, B. (2011) *Indigenous Research Methodologies*. Los Angeles.

Chilisa, G. and Kawulich, B. (2012) 'Selecting a research approach: paradigm, methodology and methods', in Wagner, C. et al. (eds) *Doing social research: a global context*. New York: McGraw-Hill Higher Education, pp. 1–21.

Choudhary, R. (2012) 'Energy analysis of the non-domestic building stock of Greater London', *Building and Environment*, 51, pp. 243–254. doi: 10.1016/J.BUILDENV.2011.10.006.

Chow, T. tai, Li, C. and Lin, Z. (2010) 'Innovative solar windows for cooling-demand climate', *Solar Energy Materials and Solar Cells*, 94(2), pp. 212–220. doi: 10.1016/j.solmat.2009.09.004.

CHPQA (2021) *'The CHPQA Standard Issue 8*. Department for Business, Energy and Industrial Strategy. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/968350/CHPQA_Standard_Issue_8.pdf.

Christensen, T. H. *et al.* (2014) 'Energy retrofits of Danish homes: is the Energy Performance Certificate useful?', *Building Research & Information*, 42(4), pp. 489–500. doi: 10.1080/09613218.2014.908265.

Chung, W. (2011) 'Review of building energy-use performance benchmarking methodologies', *Applied Energy*, 88(5), pp. 1470–1479. doi: https://doi.org/10.1016/j.apenergy.2010.11.022.

CIBSE (2004) *CIBSE Guide F: Energy efficiency in buildings*. London: Chartered Institution of Building Services Engineers.

CIBSE (2006) *Degree-days: theory and application, TM41*. London: Chartered Institution of Building Services Engineers.

CIBSE (2009) *Energy efficicency in commercial kitchens; CIBSE TM 50*. London: Chartered Institution of Building Services Engineers.

CIBSE (2012) *CIBSE Guide F: energy efficiency in buildings*. London: Chartered Institution of Building Services Engineers.

CIBSE (2015) *Environmental design, CIBSE Guide A*. London: Chartered Institution of Building Services Engineers.

CIBSE (2017a) *The Future of Heat: Non-domestic buildings, Chartered Institution of Building Services Engineers*. Available at: https://www.cibse.org/news-and-policy/consultations/current-consultations/the-future-of-heat-non-domestic-buildings (Accessed: 12 November 2020).

CIBSE (2017b) *Weather data, Chartered Institution of Building Services Engineers*. Available at: https://www.cibse.org/weatherdata (Accessed: 1 May 2021).

Cingoski, V. and Petrevska, B. (2018) 'Making hotels more energy efficient: the managerial perception', *Economic Research*, 31(1), pp. 87–101. doi: 10.1080/1331677X.2017.1421994.

Clarke, J. A., Strachan, P. A. and Pernot, C. (1993) 'Approach to the calibration of building energy simulation models', *ASHRAE Transactions*, 99(pt 2), pp. 917–927.

Climate Change Committee (2020) *The Sixth Carbon Budget: Buildings*. London. Available at: https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Buildings.pdf%0Awww.theccc.org.uk/publications.

Climate Change Committee (2021) *Progress in reducing emissions: 2021 Report to Parliament*. London. Available at: www.theccc.org.uk/publications%0Ahttps://www.theccc.org.uk/wp-content/uploads/2021/06/Progress-in-reducing-emissions-2021-Report-to-Parliament.pdf.

Cohen, R. and Bordass, B. (2015) 'Mandating transparency about building energy performance in use', *Building Research and Information*, 43(4), pp. 534–552. doi: 10.1080/09613218.2015.1017416.

Coles, T., Dinan, C. and Warren, N. (2014) 'Energy practices among small- and medium-sized tourism enterprises : a case of misdirected effort ?', *Cleaner Production*, 111(2016), pp. 399–408.

Coles, T. and Zschiegner, A. K. (2011) 'Climate change mitigation among accommodation providers in the South West of England: Comparisons between members and non-members of networks', *Tourism and Hospitality Research*, 11(2), pp. 117–132. doi: 10.1057/thr.2011.5.

Collins, R. E. and Simko, T. M. (1998) 'Current status of the science and technology of vacuum glazing', *Solar Energy*, 62(3), pp. 189–213. doi: 10.1016/S0038-092X(98)00007-3.

Committee on Climate Change (2017) *Meeting Carbon Budgets*. Available at: https://www.theccc.org.uk/publications/.

Commonwealth of Australia (2002) 'Energy efficiency opportunities in the hotel industry sector', (April), pp. 1–49.

Communities and Local Government (2018) *A User Guide to iSBEM: EPC Generation - UK*.

Costanzo, V., Evola, G. and Marletta, L. (2016) 'Thermal and visual performance of real and theoretical thermochromic glazing solutions for office buildings', *Solar Energy Materials and Solar Cells*, 149, pp. 110–120. doi: 10.1016/j.solmat.2016.01.008.

Council Directive (1993) 'COUNCIL DIRECTIVE 93/76/EEC of 13 September 1993 to limit carbon dioxide emissions by improving energy efficiency (SAVE)', *Official Journal L 237*, pp. 28–30.

Creswell, J. W. (2014) *Research Design: Qualitative, Quantitative & Mixed Methods Approaches*. Fourth. Croydon: SAGE Publications.

Creswell, J. W. and Creswell, D. (2018) *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. Los Angeles: SAGE Publications.

Crotty, M. (1998) *The foundations of social research: Meaning and perspective in the research process*. London: Sage.

Cuce, E. (2018) 'Accurate and reliable U-value assessment of argon-filled double glazed windows: A numerical and experimental investigation', *Energy and Buildings*, 171, pp. 100–106. doi: 10.1016/J.ENBUILD.2018.04.036.

Cuce, E. and Cuce, P. M. (2013) 'A comprehensive review on solar cookers', *Applied Energy*, 102, pp. 1399–1421. doi: 10.1016/j.apenergy.2012.09.002.

Cuce, E. and Riffat, S. B. (2015) 'A state-of-the-art review on innovative glazing technologies', *Renewable and Sustainable Energy Reviews*, 41, pp. 695–714. doi: 10.1016/j.rser.2014.08.084.

Cullen, J. M., Allwood, J. M. and Borgstein, E. H. (2011) 'Reducing Energy Demand: What Are the Practical Limits?', *Environmental Science and Technology*, 45(4), pp. 1711–1718. doi: 10.1021/ES102641N.

Dascalaki, E. and Balaras, C. A. (2004) 'XENIOS—a methodology for assessing refurbishment scenarios and the potential of application of RES and RUE in hotels', *Energy and Buildings*, 36(11), pp. 1091–1105. doi: https://doi.org/10.1016/j.enbuild.2004.03.007.

Dasgupta, A., Prodromou, A. and Mumovic, D. (2012) 'Operational versus designed performance of low carbon schools in England: Bridging a credibility gap', *HVAC&R Research*, 18(1–2), pp. 37–50. doi: 10.1080/10789669.2011.614318.

DBEIS (2019) *Leading on Clean Growth: The Government Response to the Committee on Climate Change's 2019 Progress Report to Parliament – Reducing UK emissions*. Department for Business, Energy and Industrial Strategy. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/839555/CCS0819884374-001_Government_Response_to_the_CCC_Progress_Report_2019_Web_Accessible.pdf.

DBEIS (2020) *Digest of United Kingdom Energy Statistics 2020*, *National Statistics*. London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/924591/DUKES_2020_MASTER.pdf.

DBEIS (2021) *Digest of UK Energy Statistics Annual data for UK, 2020*. London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1023276/DUKES_2021_Chapters_1_to_7.pdf.

DBEIS and DEFRA (2019) *Greenhouse gas reporting: conversion factors 2019*. UK Government. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2019.

DBEIS and DEFRA (2020) *Greenhouse gas reporting: conversion factors 2020*. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020 (Accessed: 7 January 2022).

DBEIS and DEFRA (2021) *Greenhouse gas reporting: conversion factors 2020*. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021 (Accessed: 7 January 2022).

DCLG (2013) *National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in England and Wales)*, *Department for Communities and local government*.

DCLG (2015) *A technical manual for SBEM*. Communities and Local Government.

Deng, S. (2003) 'Energy and water uses and their performance explanatory indicators in hotels in Hong Kong', *Energy and Buildings*, 35(8), pp. 775–784. doi: 10.1016/S0378-7788(02)00238-4.

Deng, S. M. and Burnett, J. (2000) 'Study of energy performance of hotel buildings in Hong Kong', *Energy and Buildings*, 31(1), pp. 7–12. doi: 10.1016/S0378-7788(98)00067-X.

DFIC (2016) *Cogeneration & Trigeneration – How to Produce Energy Efficiently*. Edited by S. Zellner, J. Burgtorf, and D. Kraft-Schäfer. Frankfurt: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH Programme. Available at: https://www.dfic.de/images/pdf/cogeneration-trigeneration-guide.pdf.

Díaz Pérez, F. *et al.* (2019) 'Consumption and Emissions Analysis in Domestic Hot Water Hotels. Case Study: Canary Islands', *Sustainability*, 11(3), p. 599. doi: 10.3390/su11030599.

Directive (EU) 2018/844 (2018) *Ditective (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*. doi: 10.1007/3-540-47891-4_10.

Directive 2004/8/EC (2004) *Directive 2008/104/EC of the European Parliament and of the Council of 11 February 2004 the Promotion of Cogeneration Based On a Useful Heat Demand in the Internal Energy Market and Amending Directive 92/42/EEC*, *Official Journal of the European Union*. doi: 10.1007/978-1-137-54482-7_45.

Djamel, Z. and Noureddine, Z. (2017) 'The Impact of Window Configuration on the Overall Building Energy Consumption under Specific Climate Conditions', *Energy Procedia*, 115, pp. 162–172. doi: 10.1016/j.egypro.2017.05.016.

Dorer, V. and Weber, A. (2009) 'Energy and carbon emission footprint of micro-CHP systems in residential buildings of different energy demand levels', *Journal of Building Performance Simulation*, 2(1), pp. 31–46. doi: 10.1080/19401490802596435.

van Dronkelaar, C. *et al.* (2016) 'A Review of the Regulatory Energy Performance Gap and Its Underlying Causes in Non-domestic Buildings', *Frontiers in Mechanical Engineering*, 1(January), pp. 1–14. doi: 10.3389/fmech.2015.00017.

EDSL TAS (2013) 'UK Building Regulations 2013 Studio Tutorial'. Milton Keynes: Environmental Design Solutions Ltd. Available at: https://www.edsl.net/support/.

EDSL TAS (2018) *Building Simulator Manual*. Available at: https://www.edsl.net/htmlhelp/Building_Simulator/ (Accessed: 20 April 2021).

Efficiency Valuation Organisation (2012) *International performance measurement and verification protocol. Concepts and Options for Determining Energy and Water Savings*. Oakridge, Tennessee.

EIA (1995) *COMMERCIAL BUILDINGS ENERGY CONSUMPTION SURVEY - 1995 CBECS Survey Data*. Available at: https://www.eia.gov/consumption/commercial/data/1995/.

EIA (2018) *Use of energy explained*, *U.S. Energy Information Administration*. Available at: https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php (Accessed: 23 September 2020).

EPBD (2002) *Directive 2002/65/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings*, *Official Journal of the European Communities*. doi: 10.5040/9781782258674.0021.

European Commission (2012) 'Energy Roadmap 2050', *Policy*, (April). doi: 10.2833/10759.

Fabbri, M., Groote, M. De and Rapf, O. (2016) *Building Renovation Passports: Customised roadmaps towards deep renovation and better homes*, *Buildings Performance Institute Europe*.

Fang, Y. *et al.* (2013) 'A Novel Building Component Hybrid Vacuum Glazing— A Modelling

And Experimental Validation', *ASHRAE transactions,* 119 (Part.

Farhad, S., Hamdullahpur, F. and Yoo, Y. (2010) 'Performance evaluation of different configurations of biogas-fuelled SOFC micro-CHP systems for residential applications', *International Journal of Hydrogen Energy*, 35(8), pp. 3758–3768. doi: 10.1016/j.ijhydene.2010.01.052.

Foroughi, R., Asadi, S. and Khazaeli, S. (2021) 'On the optimization of energy efficient fenestration for small commercial buildings in the United States', *Journal of Cleaner Production*, 283, p. 124604. doi: https://doi.org/10.1016/j.jclepro.2020.124604.

Fuerst, F. *et al.* (2015) 'Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England', *Energy Economics*, 48, pp. 145–156. doi: 10.1016/J.ENECO.2014.12.012.

Fuerst, F. and McAllister, P. (2011) 'The impact of Energy Performance Certificates on the rental and capital values of commercial property assets', *Energy Policy*, 39(10), pp. 6608–6614. doi: 10.1016/J.ENPOL.2011.08.005.

Fumo, N. (2014) 'A review on the basics of building energy estimation', *Renewable and Sustainable Energy Reviews*, 31, pp. 53–60. doi: https://doi.org/10.1016/j.rser.2013.11.040.

Gang, W. *et al.* (2015) 'Impacts of cooling load calculation uncertainties on the design optimization of building cooling systems', *Energy and Buildings*, 94, pp. 1–9. doi: 10.1016/J.ENBUILD.2015.02.032.

Gao, H., Koch, C. and Wu, Y. (2019) 'Building information modelling based building energy modelling: A review', *Applied Energy*, 238, pp. 320–343. doi: https://doi.org/10.1016/j.apenergy.2019.01.032.

Goeders, G. (2010) *Benchmarking of Regulations on Energy Efficiency of Buildings: Incentives and Punishments.* Available at: https://media.sitra.fi/2010/03/24103449/REHVA_Incentivesreport.pdf.

Goldner, F. S. (1994) *Energy use and domestic hot water consumption - Phase 1. Final report*. Oak Ridge, TN. doi: 10.2172/10108256.

Gorgolis, G. and Karamanis, D. (2016) 'Solar energy materials for glazing technologies', *Solar Energy Materials and Solar Cells*, 144, pp. 559–578. doi: 10.1016/J.SOLMAT.2015.09.040.

Gössling, S., Scott, D. and Hall, C. M. (2015) 'Inter-market variability in CO 2 emission-intensities in tourism : Implications for destination marketing and carbon management', *Tourism Management*, 46, pp. 203–212. doi: 10.1016/j.tourman.2014.06.021.

Government of Canada (2020) *Energy benchmarking: the basics*. Available at: https://www.nrcan.gc.ca/energy-efficiency/energy-star-canada/energy-star-buildings/energy-benchmarking-basics/18260 (Accessed: 19 September 2020).

Gram-Hanssen, K. (2014) 'Retrofitting owner-occupied housing: remember the people', *Building Research & Information*, 42(4), pp. 393–397. doi: 10.1080/09613218.2014.911572.

Gram-Hanssen, K. *et al.* (2017) 'How building regulations ignore the use of buildings , what that means for energy consumption and what to do about it', in *ECEEE Summer Study Proceedings*, pp. 2095–2104.

Gram-Hanssen, K. and Georg, S. (2018) 'Energy performance gaps: promises, people, practices', *Building Research & Information*, 46(1), pp. 1–9. doi: 10.1080/09613218.2017.1356127.

Güçyeter, B. and Günaydın, H. M. (2012) 'Optimization of an envelope retrofit strategy for an existing office building', *Energy and Buildings*, 55, pp. 647–659. doi: https://doi.org/10.1016/j.enbuild.2012.09.031.

Han, H. *et al.* (2011) 'Are lodging customers ready to go green ? An examination of attitudes , demographics , and eco-friendly intentions', *International Journal of Hospitality Management*, 30(2), pp. 345–355. doi: 10.1016/j.ijhm.2010.07.008.

Happle, G., Fonseca, J. A. and Schlueter, A. (2018) 'A review on occupant behavior in urban building energy models', *Energy and Buildings*, 174, pp. 276–292. doi: 10.1016/j.enbuild.2018.06.030.

Hardy, A. and Glew, D. (2019) 'An analysis of errors in the Energy Performance certificate database', *Energy Policy*, 129(March), pp. 1168–1178. doi: 10.1016/j.enpol.2019.03.022.

Hårsman, B., Daghbashyan, Z. and Chaudhary, P. (2016) 'On the quality and impact of residential energy performance certificates', *Energy and Buildings*, 133, pp. 711–723. doi: 10.1016/J.ENBUILD.2016.10.033.

Hashemi, A. and Khatami, N. (2015) 'The effects of air permeability, background ventilation and lifestyle on energy performance, indoor air quality and risk of condensation in domestic buildings', *Sustainability (Switzerland)*, 7(4), pp. 4022–4034. doi: 10.3390/su7044022.

Hassouneh, K., Alshboul, A. and Al-Salaymeh, A. (2010) 'Influence of windows on the energy balance of apartment buildings in Amman', *Energy Conversion and Management*, 51(8), pp. 1583–1591. doi: 10.1016/j.enconman.2009.08.037.

HELEC (2021) *Biogas CHP*. Available at: https://helec.co.uk/products/biogas-chp/ (Accessed: 29 November 2021).

Hendron, R. and Burch, J. (2007) 'Development of Standardized Domestic Hot Water Event Schedules for Residential Buildings', in *ASME 2007 Energy Sustainability Conference*. Long Beach, California: ASMEDC, pp. 531–539. doi: 10.1115/ES2007-36104.

Hiller, C. C. and Johnson, R. (2015) *Establishing benchmark levels and patterns of commercial hot water use—Hotels. Results of ASHRAE research project RP-1544*. Atlanta.

Hiller, C. C. and Johnson, R. (2017) 'Hot-Water Use in Hotels: Part 4-Comparison of Travel and Business Hotel Hot-Water System Monitoring Results', *ASHRAE Transactions*, 123(Part 2), pp. 143–159.

Hirst, E., White, D. and Goeltz, R. (1985) 'Indoor temperature changes in retrofit homes', *Energy*, 10(7), pp. 861–870. doi: https://doi.org/10.1016/0360-5442(85)90119-7.

Hjortling, C. *et al.* (2017) 'Energy mapping of existing building stock in Sweden – Analysis of data from Energy Performance Certificates', *Energy and Buildings*, 153, pp. 341–355. doi: 10.1016/J.ENBUILD.2017.06.073.

HM Government (2010) *Approved Document L2A: Conservation of fuel and power*.

HM Government (2013) *Non-Domestic Building Services Compliance Guide, NBS, part of RIBA Enterprises Ltd*. Available at: www.ribabookshops.com.

HM Government (2014) *Conservation of fuel and power. Approved Document L. Volume 2: Buildings other than dwellings*. Available at: https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l.

Hotel Energy Solutions (2011) *Key Energy Efficiency Solutions for SME Hotels*. Available at: http://www2.unwto.org/publication/key-energy-efficiency-solutions-sme-hotels.

Hueffed, A. K. and Mago, P. J. (2010) 'Influence of prime mover size and operational strategy on the performance of combined cooling, heating, and power systems under different cost structures', *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, 224(5), pp. 591–605. doi: 10.1243/09576509JPE922.

Hui, S. C. M. and Wan, M. C. . (2013) 'Study of hotel energy performance using data envelopment analysis', in *12th International Conference on Sustainable Energy technologies (SET-2013)*.

Hui, S. C. M. and Wong, M. K. F. (2010) 'Benchmarking the energy performance of hotel buildings in Hong Kong', in *Hong Kong Joint Symposium 2010*, pp. 56–69. Available at: http://web.hku.hk/~cmhui/Dalian2010?samhui.pdf.

IEA (2020) *Tracking Buildings 2020*. Available at: https://www.iea.org/reports/tracking-buildings-2020 (Accessed: 12 November 2021).

Ignite Economics (2020) *Energy Usage in the UK Hotel Industry: The Road to a Net Zero Carbon Footprint*. Available at: https://www.eea.international/wp-content/uploads/2020/10/Ignite_EEA-UK-Hotel-Energy-Report-2020.pdf.

Ingram, V., Banfill, P. F. G. and Kennedy, C. (2011) 'Towards an Objective Assessment of Energy Efficiency in Heritage Buildings', in *Proceedings of the World Renewable Energy Congress 2011*, pp. 2018–2025. doi: 10.3384/ecp110572018.

Intelligent Energy Europe (2008) *Implementing the energy performance of buildings directive. Country reports 2008*. Brussels.

IPEEC (2014) *Building Energy Rating Schemes -Assessing Issues and Impacts*. Paris, France: International Partenrship for Energy Efficiency Cooperation. Available at: http://www.ipeec.org/publications/download/id/1016.html.

Ivanko, D., Sørensen, Å. L. and Nord, N. (2021) 'Splitting measurements of the total heat demand in a hotel into domestic hot water and space heating heat use', *Energy*, 219, p. 119685. doi: https://doi.org/10.1016/j.energy.2020.119685.

Jaber, S. and Ajib, S. (2011) 'Thermal and economic windows design for different climate zones', *Energy and Buildings*, 43(11), pp. 3208–3215. doi: 10.1016/J.ENBUILD.2011.08.019.

Jelle, B. P. *et al.* (2012) 'Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities', *Solar Energy Materials and Solar Cells*, 96(1), pp. 1–28. doi: 10.1016/j.solmat.2011.08.010.

Jenkins, D., Simpson, S. and Peacock, A. (2017) 'Investigating the consistency and quality of EPC ratings and assessments', *Energy*, 138, pp. 480–489. doi: 10.1016/j.energy.2017.07.105.

Karagiorgas, M., Tsoutsos, T. and Moiá-Pol, A. (2007) 'A simulation of the energy consumption monitoring in Mediterranean hotels. Application in Greece', *Energy and Buildings*, 39(4), pp. 416–426. doi: 10.1016/j.enbuild.2006.07.008.

Karatasou, S., Santamouris, M. and Geros, V. (2006) 'Modeling and predicting building's energy use with artificial neural networks: Methods and results', *Energy and Buildings*, 38(8), pp. 949–958. doi: 10.1016/j.enbuild.2005.11.005.

Karlsson, J. and Roos, A. (2001) 'Annual energy window performance vs. glazing thermal emittance - The relevance of very low emittance values', *Thin Solid Films*, 392(2), pp. 345–348. doi: 10.1016/S0040-6090(01)01055-0.

Kassam, S. (2017) 'CIBSE response to call for evidence on The Future of Heat: Non-domestic buildings'. Chartered Institution of Building Services Engineers, pp. 1–5. Available at: https://www.cibse.org/getmedia/64c5b019-ef7c-43ba-b91a-216bea684805/Heat-non-domestic-buildings-CIBSE-response.pdf.aspx.

Kemna, R. and Moreno Acedo, J. (2014) *Average EU building heat load for HVAC equipment*. Delft. Available at: https://ec.europa.eu/energy/sites/ener/files/documents/2014_final_report_eu_building_heat_demand.pdf.

Kenton, W. (2020) *Sensitivity Analysis*. Available at: https://www.investopedia.com/terms/s/sensitivityanalysis.asp (Accessed: 7 December 2020).

Krarti, M. (2003) 'An Overview of Artificial Intelligence-Based Methods for Building Energy Systems', *Journal of Solar Energy Engineering*, 125(3), pp. 331–342. doi: 10.1115/1.1592186.

Kularatne, T. *et al.* (2019) 'Do environmentally sustainable practices make hotels more efficient? A study of major hotels in Sri Lanka', *Tourism Management*. doi: 10.1016/j.tourman.2018.09.009.

Lai, J. H. K. (2016) 'Energy use and maintenance costs of upmarket hotels', *International Journal* *of Hospitality Management*, 56, pp. 33–43. doi: 10.1016/j.ijhm.2016.04.011.

Lam, J. C. and Chan, W. W. (2003) ‘Energy performance of air-to-water and water-to-water heat pumps in hotel applications’, *Energy Conversion and Management*, 44(10), pp. 1625–1631. doi: 10.1016/S0196-8904(02)00182-6.

Lam, J. C. and Hui, S. C. M. (1996) ‘Sensitivity analysis of energy performance of office buildings’, *Building and Environment*, 31(1), pp. 27–39. doi: 10.1016/0360-1323(95)00031-3.

Laurent, M. *et al.* (2013) ‘Back to reality : How domestic energy efficiency policies in four European countries can be improved by using empirical data instead of normative calculation’, *eceee Summer Study proceedings.*, pp. 2057–2070. Available at: http://discovery.ucl.ac.uk/1403583/.

Lee, J.-S. *et al.* (2010) ‘Understanding how consumers view green hotels: how a hotel’s green image can influence behavioural intentions’, *Journal of Sustainable Tourism*, 18(7), pp. 901–914. doi: 10.1080/09669581003777747.

Lewry, A. J. *et al.* (2013) ‘Bridging the gap between operational and asset ratings-the UK experience and the green deal tool’, p. 5. Available at: https://www.bre.co.uk/filelibrary/pdf/other_pdfs/KN5477_Energy_Paper_v1.pdf.

Li, C. *et al.* (2015) ‘Experimental and theoretical study on the effect of window films on building energy consumption’, *Energy and Buildings*, 102, pp. 129–138. doi: 10.1016/j.enbuild.2015.04.025.

Li, F. G. N. *et al.* (2015) ‘Solid-wall U-values : heat flux measurements compared with standard assumptions’, *Building Research & Information*, 43(2), pp. 238–252. doi: 10.1080/09613218.2014.967977.

Li, Y. *et al.* (2019) ‘Review of building energy performance certification schemes towards future improvement’, *Renewable and Sustainable Energy Reviews*, (113), p. 109244. doi: 10.1016/j.rser.2019.109244.

Ling-Chin, J. *et al.* (2019) ‘UK building thermal performance from industrial and governmental perspectives’, *Applied Energy*, 237, pp. 270–282. doi: https://doi.org/10.1016/j.apenergy.2018.12.077.

Lomas, K. J. (1996) ‘The U.K. applicability study: an evaluation of thermal simulation programs for passive solar house design’, *Building and Environment*, 31(3), pp. 197–206. doi: https://doi.org/10.1016/0360-1323(95)00050-X.

Lu, Y. . (2008) ‘Practical design manual for heating and air conditioning’, *China Architecture and Building Press*, pp. 96–127.

Lucchi, E. (2017) ‘Thermal transmittance of historical brick masonries : A comparison among standard data , analytical calculation procedures , and in situ heat flow meter measurements’, *Energy and Buildings*, 134, pp. 171–184. doi: 10.1016/j.enbuild.2016.10.045.

Lymath, A. (2015) *What is a U-value? Heat loss, thermal mass and online calculators explained*, *NBS*. Available at: https://www.thenbs.com/knowledge/what-is-a-u-value-heat-loss-thermal-mass-and-online-calculators-explained (Accessed: 14 February 2022).

Magnani, S., Pezzola, L. and Danti, P. (2016) ‘Design Optimization of a Heat Thermal Storage Coupled with a Micro-CHP for a Residential Case Study’, *Energy Procedia*, 101(September), pp. 830–837. doi: 10.1016/j.egypro.2016.11.105.

Mago, P. J., Chamra, L. M. and Hueffed, A. (2009) ‘A review on energy, economical, and environmental benefits of the use of CHP systems for small commercial buildings for the North American climate’, *International Journal of Energy Research*, 33(14), pp. 1252–1265. doi: https://doi.org/10.1002/er.1630.

Mago, P. J., Fumo, N. and Chamra, L. M. (2009) ‘Performance analysis of CCHP and CHP systems operating following the thermal and electric load’, *International Journal of Energy Research*, 33(9), pp. 852–864. doi: https://doi.org/10.1002/er.1526.

Mago, P. J. and Luck, R. (2013) ‘Evaluation of a base-loaded combined heating and power system with thermal storage for different small building applications’, *Internationa Journal of Energy Research*, 37, pp. 179–188. doi: 10.1002/er.1892.

Mago, P. J. and Smith, A. D. (2012) ‘Evaluation of the potential emissions reductions from the use of CHP systems in different commercial buildings’, *Building and Environment*, 53, pp. 74–82. doi: 10.1016/j.buildenv.2012.01.006.

Majcen, D., Itard, L. C. M. and Visscher, H. (2013) ‘Theoretical vs. actual energy consumption of labelled dwellings in the Netherlands: Discrepancies and policy implications’, *Energy Policy*, 54, pp. 125–136. doi: 10.1016/J.ENPOL.2012.11.008.

Menezes, A. C. *et al.* (2012) ‘Predicted vs. actual energy performance of non-domestic buildings: Using post-occupancy evaluation data to reduce the performance gap’, *Applied Energy*, 97, pp. 355–364. doi: 10.1016/j.apenergy.2011.11.075.

Menicou, M. *et al.* (2015) ‘An economic analysis of Cyprus’ residential buildings’ energy retrofits potential’, *International Journal of Sustainable Energy*, 34(3–4), pp. 166–187. doi: 10.1080/14786451.2013.873800.

MHCLG (2018) *Calculating the energy performance of buildings: Notice of approval of the methodology for expressing the energy performance of buildings in England and Wales*. Ministry of Housing Communities and Local Government. Available at: https://www.gov.uk/government/publications/method-for-calculating-the-energy-performance-of-buildings-notice-of-approval.

MHCLG (2020) *Energy Performance of Buildings Certificates Statistical Release: Q1 2020 England and Wales*. London. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/882412/EPB_Cert_Statistics_Release_Q1_2020.pdf.

MHCLG (2021) *Live tables on Energy Performance of Buildings Certificates*. Available at: https://www.gov.uk/government/statistical-data-sets/live-tables-on-energy-performance-of-buildings-certificates (Accessed: 19 December 2021).

Michopoulos, A. *et al.* (2017) ‘A study on hot-water production of hotels in Cyprus: Energy and environmental considerations’, *Energy and Buildings*, 150, pp. 1–12. doi: 10.1016/j.enbuild.2017.05.071.

Milojković, A., Nikolić, M. and Stanković, V. (2012) ‘Improvement of energy efficiency in hospitality - towards sustainable hotels’, in *IV International Symposium for Students of Doctoral Studies in the Field of Civil Engineering, Architecture and Environmental Protection*, pp. 170–177.

Mirrahimi, S. *et al.* (2016) ‘The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot-humid climate’, *Renewable and Sustainable Energy Reviews*, 53, pp. 1508–1519. doi: 10.1016/j.rser.2015.09.055.

Mohelníková, J. (2011) ‘Window Glass Coatings’, in Zang, L. (ed.) *Energy Efficiency and Renewable Energy Through Nanotechnology*. London: Springer London, pp. 913–934. doi: 10.1007/978-0-85729-638-2_26.

Moiá-Pol, A. *et al.* (2006) ‘Evaluation of the Renewable Energy application in Mediterranean Hotels : Case study : the Balearic Islands’ Hotels’, *Renewable Energies and Power Quality Journal*, 1(4), pp. 106–110.

Moon, J. W. *et al.* (2015) ‘Prediction performance of an artificial neural network model for the amount of cooling energy consumption in hotel rooms’, *Energies*, 8(8), pp. 8226–8243. doi: 10.3390/en8088226.

Morant, M. (2012) *The performance gap – non domestic buildings.* Cardiff. Available at: https://www.energy-bim.com/widgets/document.php?docid=171.

Moretti, E. and Belloni, E. (2015) ‘Evaluation of energy, thermal, and daylighting performance of solar control films for a case study in moderate climate', *Building and Environment,* 94, pp. 183–195. doi: 10.1016/J.BUILDENV.2015.07.031.

Morsink-Georgali, P.-Z. and Fokaides, P. (2020) *Comparative assessment of current EPC schemes and relevant emerging building performance paradigms v1*. Nicosia, Cyprus. Available at: https://www.d2epc.eu/en.

Murakawa, S. *et al.* (2007) 'Calculation for the cold and hot water demands in the guest rooms of city hotel', in *33rd International Symposium on Water Supply and Drainage for Buildings*. Brno, Czech Republic, pp. 73–85. Available at: https://www.irbnet.de/daten/iconda/CIB6842.pdf.

Murphy, L. (2014) 'The influence of the Energy Performance Certificate: The Dutch case', *Energy Policy*, 67, pp. 664–672. doi: 10.1016/J.ENPOL.2013.11.054.

Nappi-Choulet, I. and Décamps, A. (2013) 'Capitalization of energy efficiency on corporate real estate portfolio value', *Journal of Corporate Real Estate*, 15(1), pp. 35–52. doi: 10.1108/JCRE-01-2013-0005.

Navratil, J. *et al.* (2019) 'Visitors' preferences of renewable energy options in "green" hotels', *Renewable Energy*, 138, pp. 1065–1077. doi: 10.1016/j.renene.2019.02.043.

Ng, L. C. *et al.* (2013) 'Multizone airflow models for calculating infiltration rates in commercial reference buildings', *Energy and Buildings*, 58, pp. 11–18. doi: 10.1016/j.enbuild.2012.11.035.

Nikolaou, T., Kolokotsa, D. and Stavrakakis, G. (2011) 'Review on methodologies for energy benchmarking, rating and classification of buildings', *Advances in Building Energy Research*, 5(1), pp. 53–70. doi: 10.1080/17512549.2011.582340.

Norford, L. K. *et al.* (1994) 'Two-to-one discrepancy between measured and predicted performance of a "low-energy" office building: insights from a reconciliation based on the DOE-2 model', *Energy and Buildings*, 21(2), pp. 121–131. doi: https://doi.org/10.1016/0378-7788(94)90005-1.

Oberkampf, W. L. and Roy, C. J. (2010) *Verification and Validation in Scientific Computing*. New York: Cambridge University Press.

Olaussen, J. O., Oust, A. and Solstad, J. T. (2017) 'Energy performance certificates – Informing the informed or the indifferent?', *Energy Policy*, 111(September), pp. 246–254. doi: 10.1016/j.enpol.2017.09.029.

Oluseyi, P. O., Babatunde, O. M. and Babatunde, O. A. (2016) 'Assessment of energy consumption and carbon footprint from the hotel sector within Lagos, Nigeria', *Energy and Buildings*, 118, pp. 106–113. doi: 10.1016/j.enbuild.2016.02.046.

Önüt, S. and Soner, S. (2006) 'Energy efficiency assessment for the Antalya Region hotels in Turkey', *Energy and Buildings*, 38(8), pp. 964–971. doi: 10.1016/j.enbuild.2005.11.006.

Osso, D. *et al.* (2019) 'The influence of uncertainties related to the inputs of the French EPC ' s calculation method – an analysis for individual houses', in *ECEEE 2019 Summer Study*. Presqu'île de Giens: HAL, pp. 1209–1215.

Pablo-Romero, M. del P., Pozo-Barajas, R. and Sánchez-Rivas, J. (2019) 'Tourism and temperature effects on the electricity consumption of the hospitality sector', *Journal of Cleaner Production*, 240, p. 118168. doi: 10.1016/j.jclepro.2019.118168.

Panayiota Pieri, S., Tzouvadakis, I. and Santamouris, M. (2015) 'Identifying energy consumption patterns in the Attica hotel sector using cluster analysis techniques with the aim of reducing hotels ' CO 2 footprint', *Energy & Buildings*, 94, pp. 252–262. doi: 10.1016/j.enbuild.2015.02.017.

Pang, Z. and O'Neill, Z. (2018) 'Uncertainty quantification and sensitivity analysis of the domestic hot water usage in hotels', *Applied Energy*, 232, pp. 424–442. doi: 10.1016/J.APENERGY.2018.09.221.

Parker, J., Cropper, P. and Shao, L. (2012) 'A Calibrated Whole Building Simulation Approach to Assessing Retrofit Options for Birmingham Airport', in *First Building Simulation and Optimization Conference*, pp. 49–56.

Parkinson, A. *et al.* (2013) 'Energy performance certification as a signal of workplace quality', *Energy Policy*, 62, pp. 1493–1505. doi: 10.1016/j.enpol.2013.07.043.

Pasichnyi, O. *et al.* (2019) 'Energy performance certificates — New opportunities for data-enabled urban energy policy instruments?', *Energy Policy*, 127(April 2018), pp. 486–499. doi: 10.1016/j.enpol.2018.11.051.

Pederson, C. ., Fisher, D. . and Liesen, R. J. (1997) 'Development of a Heat Development of a Heat Balance Procedure for Calculating Cooling Loads', *ASHRAE Transactions*, 103, pp. 459–468. Available at: www.ashrae.org (Accessed: 13 July 2021).

Pegg, I., Cripps, A. and Kolokotroni, M. (2007) 'Post-occupancy performance of five low-energy schools in the UK', *ASHRAE Transactions*, 113(Part 2). Available at: https://search.proquest.com/openview/6fc98cbe9b8773acb6beab67e16e93e1/1?pq-origsite=gscholar&cbl=34619.

Pérez-Lombard, L. *et al.* (2009) 'A review of benchmarking, rating and labelling concepts within the framework of building energy certification schemes', *Energy and Buildings*, 41(3), pp. 272–278. doi: 10.1016/j.enbuild.2008.10.004.

Petersen, S. and Hviid, C. A. (2012) 'The European Energy Performance of Buildings Directive: Comparison of Calculated and Actual Energy Use in a Danish Office Building', in *Building Simulation and Optimization Conference*, pp. 43–48.

Pieri, S. P., IoannisTzouvadakis and Santamouris, M. (2015) 'Identifying energy consumption patterns in the Attica hotel sector using cluster analysis techniques with the aim of reducing hotels' CO2 footprint', *Energy and Buildings*, 94, pp. 252–262. doi: 10.1016/j.enbuild.2015.02.017.

von Platten, J. *et al.* (2019) 'The renewing of Energy Performance Certificates—Reaching comparability between decade-apart energy records', *Applied Energy*, 255(July), p. 113902. doi: 10.1016/j.apenergy.2019.113902.

Pritchard, R. and Kelly, S. (2017) 'Realising operational energy performance in non-domestic buildings: Lessons learnt from initiatives applied in Cambridge', *Sustainability (Switzerland)*, 9(8). doi: 10.3390/su9081345.

Priyadarsini, R., Xuchao, W. and Eang, L. S. (2009) 'A study on energy performance of hotel buildings in Singapore', *Energy and Buildings*, 41(12), pp. 1319–1324. doi: 10.1016/j.enbuild.2009.07.028.

Raftery, P., Keane, M. and Costa, A. (2011) 'Calibrating whole building energy models: Detailed case study using hourly measured data', *Energy and Buildings*, 43(12), pp. 3666–3679. doi: 10.1016/j.enbuild.2011.09.039.

Ralegaonkar, R. V. and Gupta, R. (2010) 'Review of intelligent building construction: A passive solar architecture approach', *Renewable and Sustainable Energy Reviews*, 14(8), pp. 2238–2242. doi: 10.1016/j.rser.2010.04.016.

Raslan, R. and Davies, M. (2010) 'Results variability in accredited building energy performance compliance demonstration software in the UK: an inter-model comparative study', *Journal of Building Performance Simulation*, 3(1), pp. 63–85. doi: 10.1080/19401490903477386.

Raslan, R. and Davies, M. (2012) 'Legislating building energy performance: putting EU policy into practice', *Building Research & Information*, 40(3), pp. 305–316. doi: 10.1080/09613218.2012.681440.

Recast EPBD (2010) *Directive 2010/31/EU of the European Parliment and of the Council of 19 MAY on the enrgy performance of the buildings (recast)*. 18. 06.

Rezaei, S. D., Shannigrahi, S. and Ramakrishna, S. (2017) ‘A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment’, *Solar Energy Materials and Solar Cells*, 159, pp. 26–51. doi: 10.1016/j.solmat.2016.08.026.

Roberts, S. (2008) ‘Altering existing buildings in the UK’, *Energy Policy*, 36, pp. 4482–4486. doi: 10.1016/j.enpol.2008.09.023.

Rosselló-Batle, B. *et al.* (2010) ‘Energy use, CO2emissions and waste throughout the life cycle of a sample of hotels in the Balearic Islands’, *Energy and Buildings*, 42(4), pp. 547–558. doi: 10.1016/j.enbuild.2009.10.024.

Rotimi, A. *et al.* (2017) ‘Estimation and Validation of Energy Consumption in UK Existing Hotel Building Using Dynamic Simulation Software’, *Sustainability (Switzerland)*, 9(8). doi: 10.3390/su9081391.

Rotimi, A. *et al.* (2018) ‘Optimum Size Selection of CHP Retrofitting in Existing UK Hotel Building’, *Sustainability (Switzerland)*, pp. 1–17. doi: 10.3390/su10062044.

van Ruijven, B. J., De Cian, E. and Sue Wing, I. (2019) ‘Amplification of future energy demand growth due to climate change’, *Nature Communications*, 10(1), p. 2762. doi: 10.1038/s41467-019-10399-3.

Salem, R. *et al.* (2018) ‘Comparison and Evaluation of the Potential Energy, Carbon Emissions, and Financial Impacts from the Incorporation of CHP and CCHP systems in Existing UK Hotel Buildings’, *Energies*, 11(5), pp. 1–15. doi: 10.3390/en11051219.

Salem, R. *et al.* (2019) ‘Life Cycle Cost Analysis of Retrofit Scenarios for a UK Residential Dwelling’, *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, (June), pp. 1–14. doi: 10.1680/jensu.18.00055.

Salem, R., Bahadori-Jahromi, A. and Mylona, A. (2019) ‘Investigating the impacts of a changing climate on the risk of overheating and energy performance for a UK retirement village adapted to the nZEB standards’, *Building Services Engineering Research and Technology*, 40(4), pp. 470–491. doi: 10.1177/0143624419844753.

Santamouris, M. *et al.* (1996) ‘Energy conservation and retrofitting potential in Hellenic hotels’, *Energy and Buildings*, 24(September 1995), pp. 65–75.

Sayce, S. and Hossain, S. M. (2020) *Minimum Energy Efficiency Standards One year on : a progress report, School of Real Estate and Planning, Henley Business School*. Available at: https://assets.henley.ac.uk/defaultUploads/MEES-RREF-Report.pdf.

Semple, S. and Jenkins, D. (2020) ‘Variation of energy performance certificate assessments in the European Union’, *Energy Policy*, 137, p. 111127. doi: 10.1016/j.enpol.2019.111127.

Sesana, M. M. and Salvalai, G. (2018) ‘A review on Building Renovation Passport: Potentialities and barriers on current initiatives’, *Energy and Buildings*, 173, pp. 195–205. doi: 10.1016/j.enbuild.2018.05.027.

Sheng, Y. *et al.* (2018) ‘Energy consumption model and energy benchmarks of five-star hotels in China’, *Energy and Buildings*, 165, pp. 286–292. doi: 10.1016/j.enbuild.2018.01.031.

Shenton Group (2021) *Combined heat and power systems*. Available at: https://www.shentongroup.co.uk/wp-content/uploads/2021/09/CHP-data-2021.pdf (Accessed: 2 October 2021).

Smitt, S. *et al.* (2021) ‘Energy use and retrofitting potential of heat pumps in cold climate hotels’, *Journal of Cleaner Production*, 298, p. 126799. doi: 10.1016/j.jclepro.2021.126799.

Souayfane, F., Fardoun, F. and Biwole, P.-H. (2016) ‘Phase change materials (PCM) for cooling applications in buildings: A review’, *Energy and Buildings*, 129, pp. 396–431. doi: 10.1016/j.enbuild.2016.04.006.

Sousa, G. *et al.* (2017) 'A review and critique of UK housing stock energy models, modelling approaches and data sources', *Energy and Buildings*, 151, pp. 66–80. doi: 10.1016/j.enbuild.2017.06.043.

Stein, J. R. and Meier, A. (2000) 'Accuracy of home energy rating systems', *Energy*, 25(4), pp. 339–354. doi: 10.1016/S0360-5442(99)00072-9.

Stone, A. *et al.* (2014) 'Key factors determining the energy rating of existing English houses', *Building Research and Information*, 42(6), pp. 725–738. doi: 10.1080/09613218.2014.905383.

Styles, D., Schönberger, H. and Galvez Martos, J. L. (2013) 'Minimising Energy Use in Tourist Accommodation', in *Best Environmental Management Practice in The Tourism Sector*. Seville: Joint Research Center. doi: 10.2788/33972.

Summerfield, A. J. *et al.* (2019) 'What do empirical findings reveal about modelled energy demand and energy ratings? Comparisons of gas consumption across the English residential sector', *Energy Policy*, 129(February), pp. 997–1007. doi: 10.1016/j.enpol.2019.02.033.

Sun, Y. (2015) 'Sensitivity analysis of macro-parameters in the system design of net zero energy building', *Energy and Buildings*, 86, pp. 464–477. doi: 10.1016/j.enbuild.2014.10.031.

Sunikka-Blank, M. and Galvin, R. (2012) 'Introducing the prebound effect: The gap between performance and actual energy consumption', *Building Research and Information*, 40(3), pp. 260–273. doi: 10.1080/09613218.2012.690952.

Surmann, M., Brunauer, W. and Bienert, S. (2015) 'How does energy efficiency influence the Market Value of office buildings in Germany and does this effect increase over time?', *Journal of European Real Estate Research*, 8(3), pp. 243–266. doi: 10.1108/JERER-04-2015-0018.

Sutherland, G. *et al.* (2016) *Implementing the Energy Performance of Buildings Directive (EPBD) – Part A, Climate Change 2013 - The Physical Science Basis*. Lisbon: Concerted Action. Energy Performance Building directive. Available at: http://www.buildup.eu/en/practices/publications/2016-implementing-energy-performance-buildings-directive-epbd-part.

Sweitzer, G., Arasteh, D. and Selkowitz, S. (1987) 'Effects of low-emissivity glazings on energy use patterns in nonresidential daylighted buildings', *ASHRAE transactions*, (93 (Part 1)).

Taylor, S. *et al.* (2010) 'Reduction of greenhouse gas emissions from UK hotels in 2030', *Building and Environment*, 45(6), pp. 1389–1400. doi: 10.1016/j.buildenv.2009.12.001.

Teng, C. C. *et al.* (2012) 'Developing energy conservation and carbon reduction indicators for the hotel industry in Taiwan', *International Journal of Hospitality Management*, 31(1), pp. 199–208. doi: 10.1016/j.ijhm.2011.06.006.

Teng, Z. R., Wu, C. Y. and Xu, Z. Z. (2017) 'New energy benchmarking model for budget hotels', *International Journal of Hospitality Management*, 67, pp. 62–71. doi: 10.1016/j.ijhm.2017.07.010.

Thompson, D. *et al.* (2021) 'Managing the risk of the energy performance gap in non-domestic buildings', *Building Services Engineering Research and Technology*, 43(1), pp. 57–88. doi: 10.1177/01436244211008319.

Tigchelaar, C., Daniels, B. and Menkveld, M. (2011) 'Obligations in the existing housing stock : who pays the bill?', in *ECEEE 2011 Summer Study. ENERGY EFFICIENCY FIRST: THE FOUNDATION OF A LOW-CARBON SOCIETY*. Belambra Presquile de Giens, France, pp. 353–363.

Todorović, D. *et al.* (2020) 'A comparative analysis of a heat pump application with grey wastewater source for domestic hot water preparation in hotels', *Journal of Thermal Analysis and Calorimetry*, 141(1), pp. 559–572. doi: 10.1007/s10973-020-09495-0.

Toleikyte, A. *et al.* (2016) *ZEBRA 2020 - NEARLY ZERO-ENERGY BUILDING STRATEGY 2020 Strategies for a nearly Zero-Energy Building market transition in the European Union*. Intelligent Energy Europe Programme of the European Union. Available at: https://sintef.brage.unit.no/sintef-xmlui/bitstream/handle/11250/2427773/ZEBRA2020_Strategies-for-nZEB_07_LQ_single-pages-

1.pdf?sequence=1.

Tronchin, L. and Fabbri, K. (2012) ‘Energy Performance Certificate of building and confidence interval in assessment: An Italian case study’, *Energy Policy*, 48, pp. 176–184. doi: 10.1016/J.ENPOL.2012.05.011.

Udawatta, L., Perera, A. and Witharana, S. (2010) ‘Analysis of sensory information for efficient operation of energy management systems in commercial hotels’, *Electronic Journal of Structural Engineering*, EJSE S, pp. 113–120.

UK Government (2010) *The Building Regulations 2010. Approved Document L2A Conservation of fuel and power in new buildings other than dwellings, Conservation of fuel and power*. Available at: http://www.planningportal.gov.uk/uploads/br/BR_PDF_ADL2A_2010.pdf.

UK Government (2021) *UK enshrines new target in law to slash emissions by 78% by 2035, Department for Business, Energy & Industrial Strategy*. Available at: https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035 (Accessed: 30 December 2021).

Urbikain, M. K. and Sala, J. M. (2009) ‘Analysis of different models to estimate energy savings related to windows in residential buildings’, *Energy and Buildings*, 41(6), pp. 687–695. doi: 10.1016/j.enbuild.2009.01.007.

Ürge-Vorsatz, D. *et al.* (2012) ‘Chapter 10 - Energy End-Use: Building’, in *Global Energy Assessment - Toward a Sustainable Future*. Cambridge: Cambridge University Press, pp. 649–760. Available at: https://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Chapters_Home.en.html.

US Department of Energy (2015) *M & V Guidelines : Measurement and Verification for Contracts*. Available at: https://www.energy.gov/eere/femp/downloads/mv-guidelines-measurement-and-verification-performance-based-contracts-version.

Volt, J. *et al.* (2020) *X-tendo: Energy Performance Certificates, Assessing Their Status and Potential*. Available at: https://x-tendo.eu/.

Wang, D., Meng, J. and Zhang, T. (2021) ‘Post-evaluation on energy saving reconstruction for hotel buildings, a case study in Jiangsu, China’, *Energy and Buildings*, 251, p. 111316. doi: 10.1016/j.enbuild.2021.111316.

Wang, H. *et al.* (2015) ‘Modelling and optimization of CHP based district heating system with renewable energy production and energy storage’, *Applied Energy*, 159, pp. 401–421. doi: 10.1016/j.apenergy.2015.09.020.

Wang, J. (Jialiang) and Shi, D. (2017) ‘Spectral selective and photothermal nano structured thin films for energy efficient windows’, *Applied Energy*, 208, pp. 83–96. doi: 10.1016/J.APENERGY.2017.10.066.

Wang, J. C. (2012) ‘A study on the energy performance of hotel buildings in Taiwan’, *Energy and Buildings*, 49, pp. 268–275. doi: 10.1016/j.enbuild.2012.02.016.

Waters, L. (2021) ‘Combined Heat and Power (CHP)’, in *Digest of UK Energy Statistics Annual data for UK, 2020*. Department for Business, Energy and Industrial Strategy. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1023276/DUKES_2021_Chapters_1_to_7.pdf.

Watts, C., Jentsch, M. F. and James, P. A. (2011) ‘Evaluation of domestic Energy Performance Certificates in use’, *Building Services Engineering Research and Technology*, 32(4), pp. 361–376. doi: 10.1177/0143624411404486.

de Wilde, P. (2014) ‘The gap between predicted and measured energy performance of buildings: A framework for investigation’, *Automation in Construction*, 41, pp. 40–49. doi: 10.1016/j.autcon.2014.02.009.

Williamson, J. B. (2012) *The gap between design & build: construction compliance towards 2020 in Scotland*. Edinburgh.

WTO (2011) *Best Practices Guide: Successful Energy Efficiency Technologies Integration in SME Hotels*. Madrid, Spain.

Xing, J., Ren, P. and Ling, J. (2015) 'Analysis of energy efficiency retrofit scheme for hotel buildings using eQuest software: A case study from Tianjin, China', *Energy and Buildings*, 87, pp. 14–24. doi: 10.1016/j.enbuild.2014.10.045.

Yao, Z., Zhuang, Z. and Gu, W. (2015) 'Study on Energy Use Characteristics of Hotel Buildings in Shanghai', *Procedia Engineering*, 121, pp. 1977–1982. doi: 10.1016/j.proeng.2015.09.195.

Ye, H. *et al.* (2013) 'The route to a perfect window', *Renewable Energy*, 55, pp. 448–455. doi: 10.1016/j.renene.2013.01.003.

Yin, R., Xu, P. and Shen, P. (2012) 'Case study: Energy savings from solar window film in two commercial buildings in Shanghai', *Energy and Buildings*, 45, pp. 132–140. doi: 10.1016/J.ENBUILD.2011.10.062.

Zhao, H. X. and Magoulès, F. (2012) 'A review on the prediction of building energy consumption', *Renewable and Sustainable Energy Reviews*, 16(6), pp. 3586–3592. doi: 10.1016/j.rser.2012.02.049.

Zheng, Y. and Weng, Q. (2019) 'Modeling the effect of climate change on building energy demand in Los Angeles county by using a GIS-based high spatial- and temporal-resolution approach', *Energy*, 176, pp. 641–655. doi: 10.1016/j.energy.2019.04.052.

Zmeureanu, R. G. *et al.* (1994) 'Energy performance of hotels in Ottawa', *ASHRAE transactions*, 100(1), pp. 314–322.

Zou, P. X. W. *et al.* (2018) 'Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives', *Energy and Buildings*, 178, pp. 165–181. doi: 10.1016/j.enbuild.2018.08.040.

Appendix A

The values for estimated water consumption in Tables 6.7–6.10 of chapter 6 are based on 100% occupancy for guest rooms. The following Tables show the estimated water consumption for guest rooms based on the average occupancy from measured data.

- Guest room area for Hilton Reading: 5279.061 m^2
- Guest room area for DT Docklands: 9591.523 m^2
- Guest room area for Hilton Watford: 4760.072 m^2

Hilton Reading	2016		2017		2018		Predicted DHW consumption for the guest rooms based on NCM assumption of 13.12 l/d/m² for 100% occupancy rate	Average occupancy rate (%) during 2016–2018	Predicted DHW consumption for the guest rooms based on NCM assumption of 13.12 l/d/m² for average occupancy rate
	Water consumption (l)	Occupancy rate (%)	Water consumption (l)	Occupancy rate (%)	Water consumption (l)	Occupancy rate (%)			
Jan	760,998.56	64.76	1,018,998.08	69.69	69.69 983,998.14	70.28	2,147,099.69	66.82	1,434,697.95
Feb	1,483,997.20	75.09	956,998.19	74.57	1,022,998.07	69.60	1,939,315.85	74.21	1,439,239.55
Mar	635,998.80	72.38	996,998.12	74.85	993,998.12	81.98	2,147,099.69	73.61	1,580,586.39
Apr	1,146,997.83	75.78	1,047,998.02	73.16	1,042,998.03	74.40	2,077,838.41	75.51	1,568,932.91
May	1,047,998.02	76.79	1,015,998.08	80.41	985,998.14	78.45	2,147,099.69	77.21	1,657,763.25
Jun	1,707,996.77	88.24	1,163,997.80	83.54	1,032,998.05	84.52	2,077,838.41	84.63	1,758,576.89
Jul	723,998.63	87.17	1,290,724.83	83.47	1,612,996.95	82.13	2,147,099.69	85.05	1,826,189.09
Aug	1,276,997.59	88.96	1,193,970.47	81.71	1,303,997.54	74.42	2,147,099.69	83.04	1,782,873.31
Sep	1,317,997.51	85.84	1,114,197.90	80.02	1,148,997.83	77.59	2,077,838.41	80.08	1,664,029.74
Oct	1,382,997.39	80.83	1,112,097.90	79.08	1,186,997.76	73.61	2,147,099.69	80.63	1,731,202.19
Nov	1,230,997.67	77.79	1,222,297.69	78.78	1,174,997.78	72.98	2,077,838.41	75.39	1,566,514.26
Dec	743,998.59	68.94	884,998.33	67.37	1,210,997.71	66.01	2,147,099.69	68.86	1,478,563.43
Total	13,460,974.58		13,019,275.41		13,701,974.12		25,280,367.32		19,489,168.95
Hot water	6,730,487.29		6,509,637.71		6,850,987.06				

DT Docklands	2016		2017		2018		Predicted DHW consumption for the guest rooms based on NCM assumption of 13.12 l/d/m² for 100% occupancy rate	Average occupancy rate (%) during 2016–2018	Predicted DHW consumption for the guest rooms based on NCM assumption of 13.12 l/d/m² for average occupancy rate
	Water consumption (l)	Occupancy rate (%)	Water consumption (l)	Occupancy rate (%)	Water consumption (l)	Occupancy rate (%)			
Jan	4,328,991.82	58.39	1,852,996.50	63.65	2,357,995.55	56.75	3,901,064.23	59.59	2,324,836.31
Feb	3,974,992.49	71.26	2,204,995.84	73.33	2,737,994.83	75.43	3,523,541.89	73.34	2,584,132.76
Mar	3,890,992.65	61.97	2,281,995.69	74.71	3,339,993.69	77.37	3,901,064.23	71.35	2,783,478.24
Apr	2,521,995.24	73.02	2,930,994.46	73.64	2,583,995.12	78.34	3,775,223.45	75.00	2,831,417.59
May	4,046,992.36	75.22	2,727,994.85	79.78	3,048,994.24	81.79	3,901,064.23	78.93	3,079,104.21
Jun	3,874,992.68	77.41	4,087,992.28	81.00	3,521,993.35	90.44	3,775,223.45	82.95	3,131,482.38
Jul	2,932,994.46	84.58	1,904,996.40	83.88	7,446,985.93	91.06	3,901,064.23	86.51	3,374,619.20
Aug	2,932,994.46	74.48	2,493,995.29	71.36	2,879,994.56	87.82	3,901,064.23	77.89	3,038,488.93
Sep	2,800,994.71	85.29	2,397,995.47	79.25	2,537,995.21	88.47	3,775,223.45	84.34	3,183,860.56
Oct	2,365,995.53	77.52	2,843,994.63	79.78	2,819,994.67	89.36	3,901,064.23	82.22	3,207,497.32
Nov	2,366,995.53	86.50	2,551,995.18	79.33	2,722,994.86	86.18	3,775,223.45	84.00	3,171,320.87
Dec	2,369,995.52	72.24	3,115,994.11	69.45	2,085,996.06	69.73	3,901,064.23	70.47	2,749,188.30
Total	38,408,927.46		31,395,940.70		38,084,928.07		45,931,885.34		35,459,426.66
Hot water	19,204,463.73		15,697,970.35		19,042,464.03				

Hilton Watford	2016		2017		2018		Predicted DHW consumption for the guest rooms based on NCM assumption of 13.12 l/d/m² for 100% occupancy rate	Average occupancy rate (%) during 2016–2018	Predicted DHW consumption for the guest rooms based on NCM assumption of 13.12 l/d/m² for average occupancy rate
	Water consumption (l)	Occupancy rate (%)	Water consumption (l)	Occupancy rate (%)	Water consumption (l)	Occupancy rate (%)			
Jan	1,781,996.63	70.71	1,234,997.67	75.55	1,193,997.74	71.73	1,936,016.484	72.66	1,406,734.56
Feb	2,050,996.13	78.09	1,287,997.57	79.50	1,276,997.59	77.59	1,748,660.05	78.39	1,370,806.63
Mar	2,658,994.98	77.08	1,755,996.68	74.94	1,505,997.16	74.02	1,936,016.484	75.34	1,458,673.92
Apr	1,523,997.12	80.43	909,998.28	70.25	1,420,997.32	74.45	1,873,564.339	75.04	1,406,005.95
May	1,510,997.15	79.44	1,391,997.37	83.06	1,345,997.46	81.21	1,936,016.484	81.24	1,572,753.18
Jun	1,746,996.70	83.22	1,400,997.35	78.17	1,372,997.41	78.87	1,873,564.339	80.08	1,500,412.77
Jul	1,507,997.15	89.73	1,387,997.38	83.89	1,801,996.60	87.08	1,936,016.484	86.90	1,682,356.69
Aug	1,659,996.86	86.68	1,578,997.02	84.55	1,968,996.28	90.65	1,936,016.484	87.29	1,689,955.03
Sep	1,539,997.09	83.57	1,344,997.46	79.73	1,391,997.37	84.98	1,873,564.339	82.76	1,550,582.66
Oct	1,274,997.59	82.81	1,337,997.47	76.11	1,391,997.37	87.19	1,936,016.484	82.04	1,588,262.13
Nov	1,360,997.43	82.13	1,539,997.09	76.95	1,628,996.92	82.43	1,873,564.339	80.51	1,508,323.38
Dec	1,495,997.17	73.77	1,276,997.59	69.76	1,323,997.50	74.06	1,936,016.484	72.53	1,404,236.47
Total	20,113,962.00		16,448,968.93		17,624,966.72		22,795,032.79		18,139,103.38
Hot water	10,056,981.00		8,224,484.47		8,812,483.36				